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Flexible Large Area Electronics and Photonics

From Electronics Only There to Electronics Everywhere

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Acknowledgements

Current Jackson Group members:

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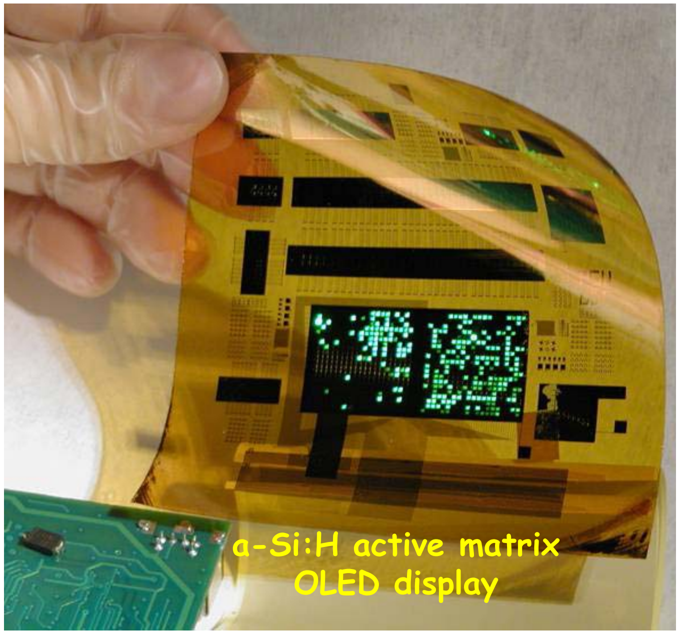
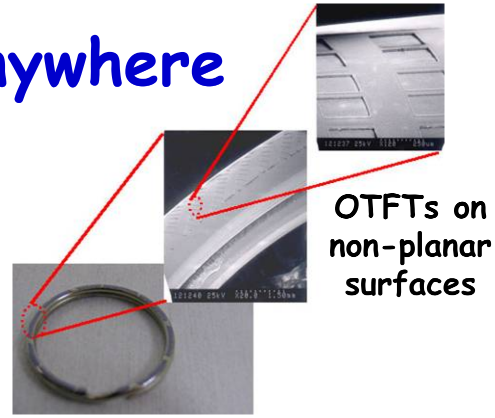
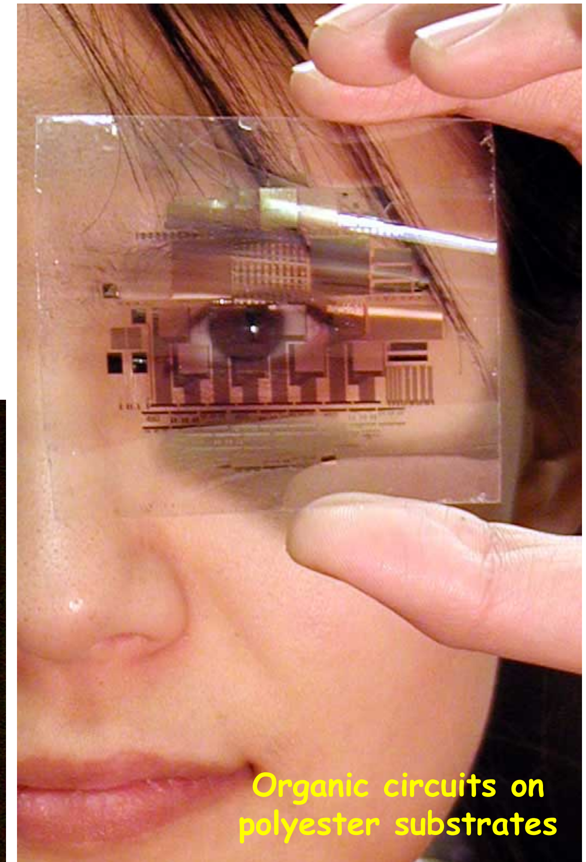
- Ph.D. students: Bo Bai, Ying-Ming Huang, Hyunsoo Kim, Sung Kyu Park, Matt Smith, Jie Sun, Yi Zhang, Dalong Zhao, Lisong Zhou
- M.S. students: Ho Him Raymond Fok, Arhan Gunel
- Undergraduates: Sudhanshu Gakhar

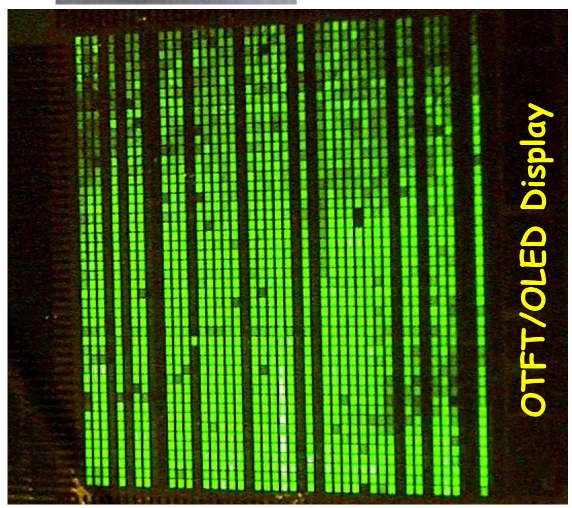
Low-cost devices and circuits on arbitrary substrates

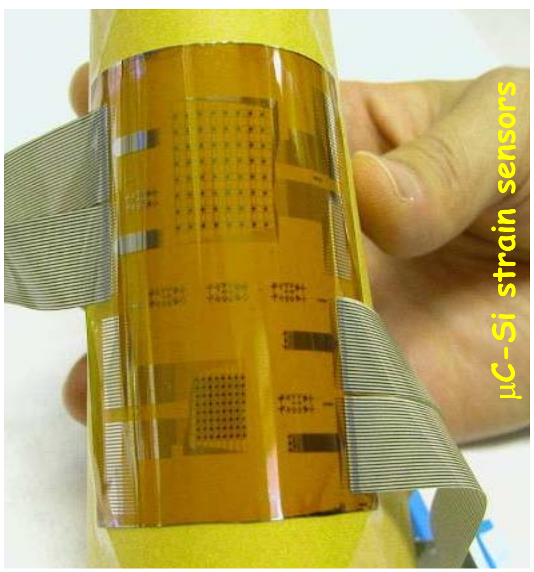
Electronics anywhere

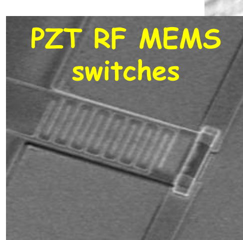












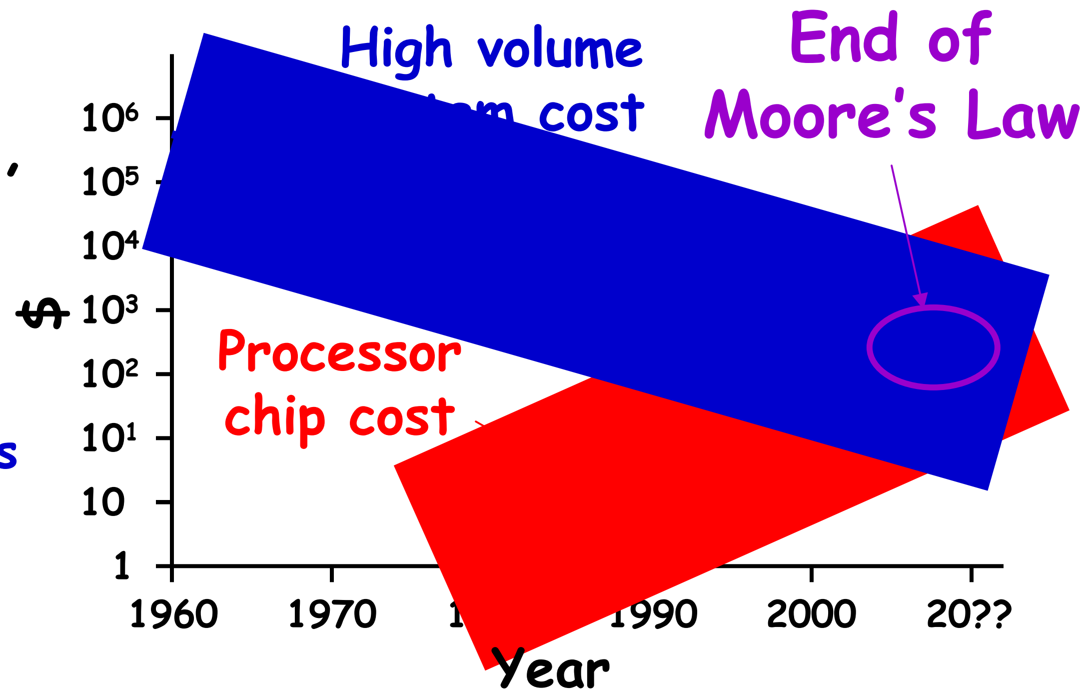
Moore's Law – The End

Moore's law is now largely irrelevant

Increasingly, computation, control, communication, et cetera are "free" on the scale of the problem being solved

Furthermore, it's ending

Forget the red brick wall, worry about Maly's law



Clarke's first law:

When a distinguished but elderly scientist states that something is possible he is almost certainly right. When he states that something is impossible, he is very probably wrong.

Arthur C. Clarke in *Profiles of the Future*

Elderly: In physics, mathematics and astronautics it means over thirty; in other disciplines, senile decay is sometimes postponed to the forties. There are of course, glorious exceptions; but as every researcher just out of college knows, scientists of over fifty are good for nothing but board meetings, and should at all costs be kept out of the laboratory.

Arthur C. Clarke in *Profiles of the Future*

*** Wojciech P. Maly, Carnegie Mellon University**

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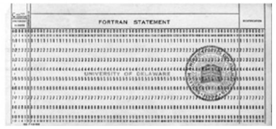
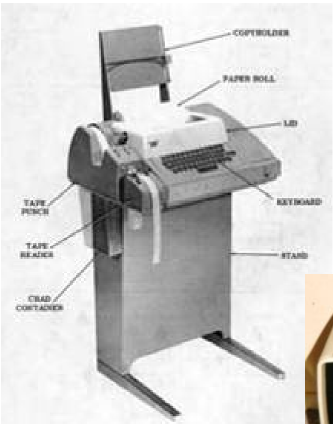
Moore’s Law Alternatives ⇒ New Electronic Progress

Example: displays





Primordial ooze

CGA
320x200
4 colors

EGA
640x350
16 colors

VGA
640x480
16 colors

XGA
1024x768
16b color

SXGA
1280x1024
32b color

UXGA
1600x1200
32b color

WUXGA
1920x1200
32b color

QWUXGA
3840x2400
32b color

Samsung 82”, HDTV, ~12.5×10^{6} TFTs

For thin film electronics the future is here

Yearly area of semiconductor electronics in active matrix displays exceeds IC area

Amorphous silicon is now second only to single crystal silicon in economic importance (far beyond III-Vs, SiGe, et cetera)

New Samsung Gen VII display line (one factory) will produce an area of active electronics equal to ~10% of the worldwide total IC area

60,000 1870 mm x 2200 mm panels/month
~3 × 10^6 m^2/year (~730 acres)
~0.1 m^2/s of finished work
~5 × 10^6 kg of glass/year

N.B.: for flexible large area electronics and photonics this is the competition

Paradigm Shift

Old paradigm: bring the problem to solution in single crystal semiconductors

New paradigm: take the microelectronic solution to the problem

To take the solution to the problem:

- **size matters**
- **form factor matters**
- **material matters**
- **process matters**
- **function matters**
- **cost matters matters matters**

Performance is determined by application and context

Cost and Process as Drivers

Example: Smart dressing

Sense:

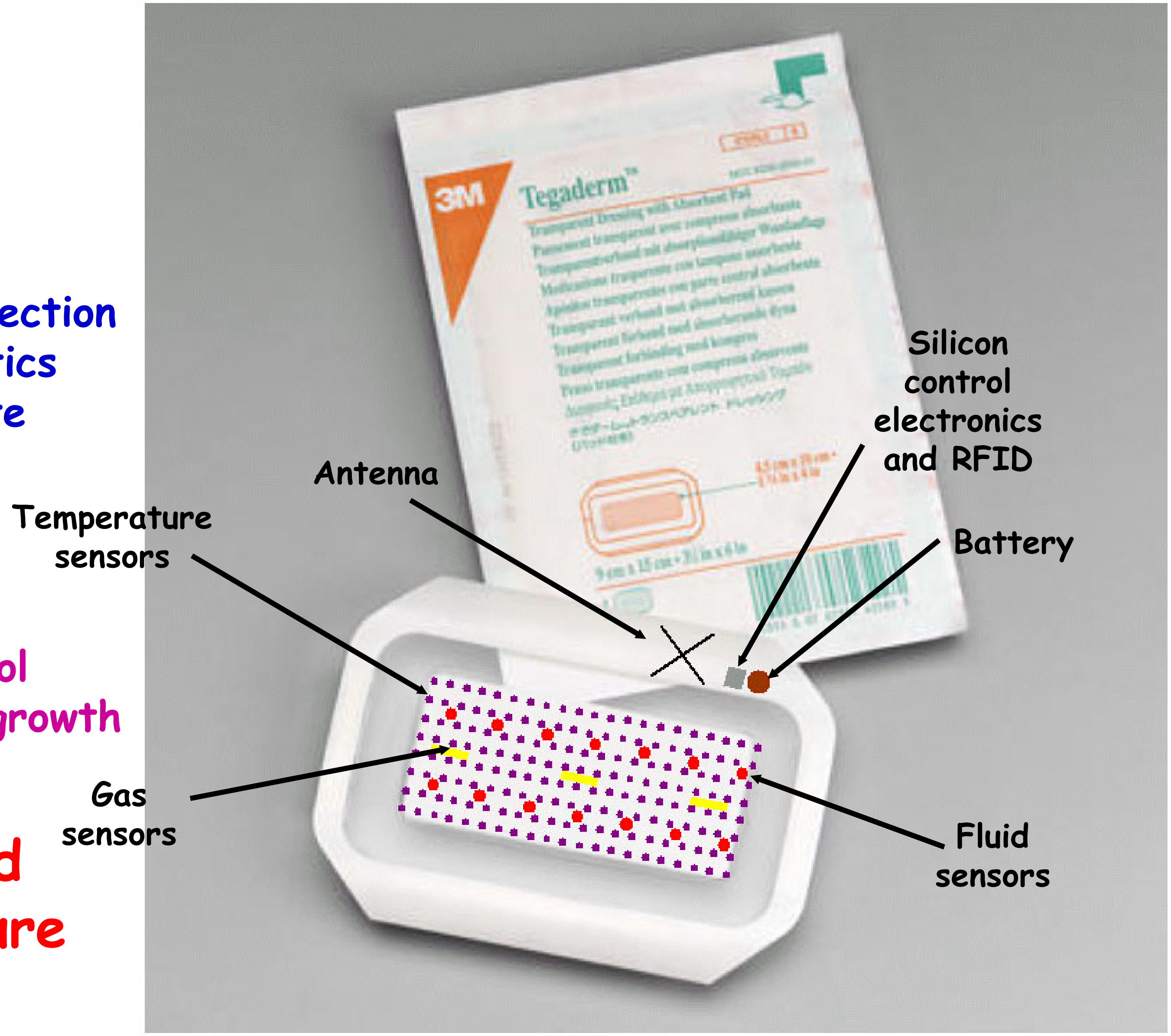
- Infection
- Leakage
- Rejection

- Early problem detection
- Improved diagnostics
- Reduced error rate
- Improved system integration

Active therapy:

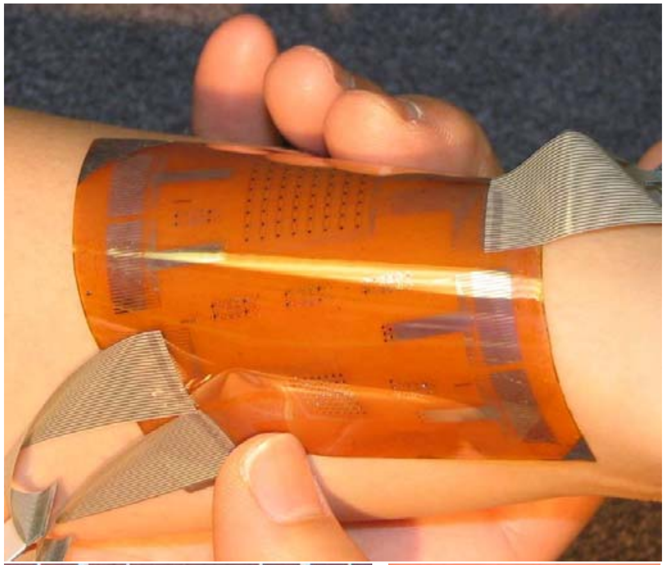
- Local drug control
- Stimulated cell growth

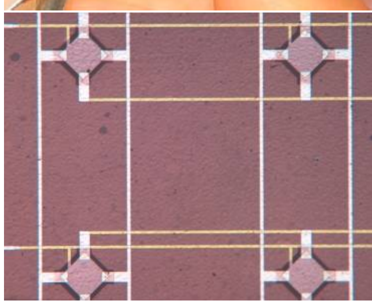
Low-cost and low-temperature are drivers



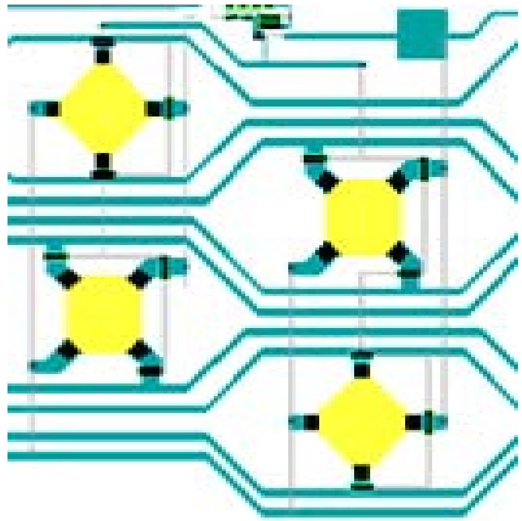
Size Matters

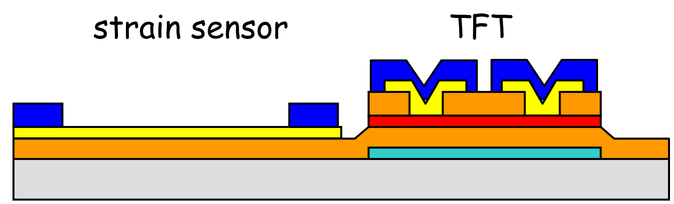
Example: sensor arrays





- Flexible semiconductor strain sensor
- TFTs for sensor selection and isolation
- Large area shape and strain sensing
- Structural health monitoring
- Many other sensor types possible

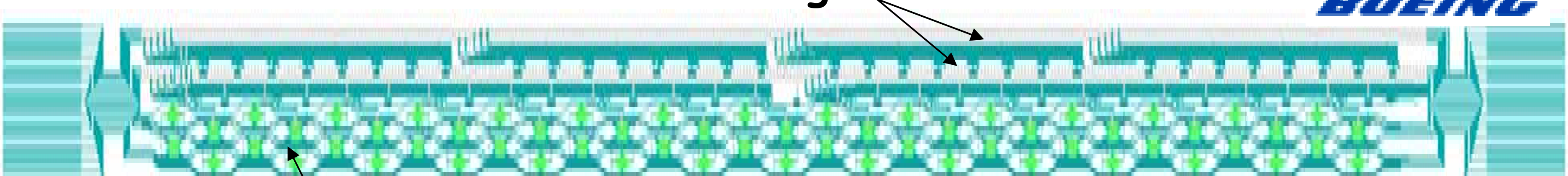




100" demo
100' application

BOEING

sensor select decode logic



strain sensors (15 columns of 4 sensors)

Jet Propulsion Laboratory
California Institute of Technology

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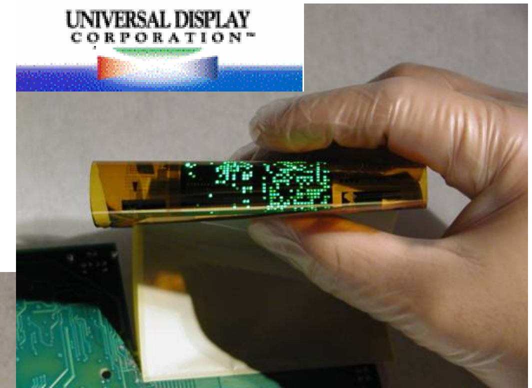
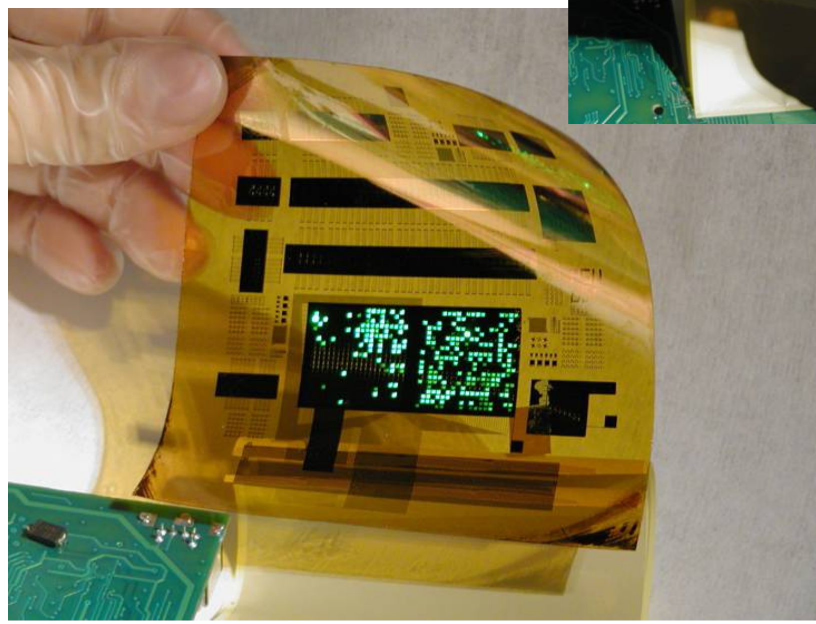
1855

Form Factor Matters

Example: Displays





Light-weight, rugged, flexible displays

Displays on curved and arbitrary surfaces

Advantages for sensor arrays similar

NEXTGEN AERONAUTICS
Inventing Technologies for the Next 100 Years of Flight

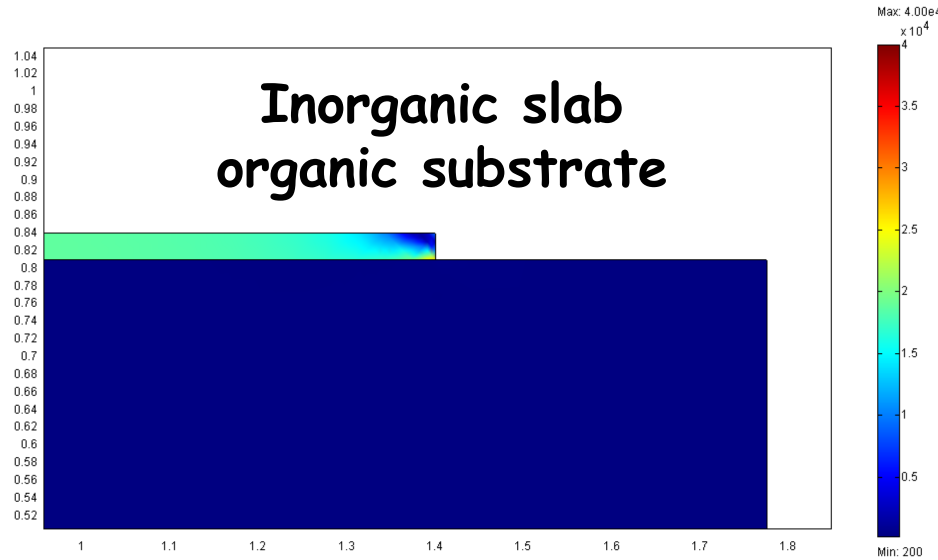
Example: Soft Materials

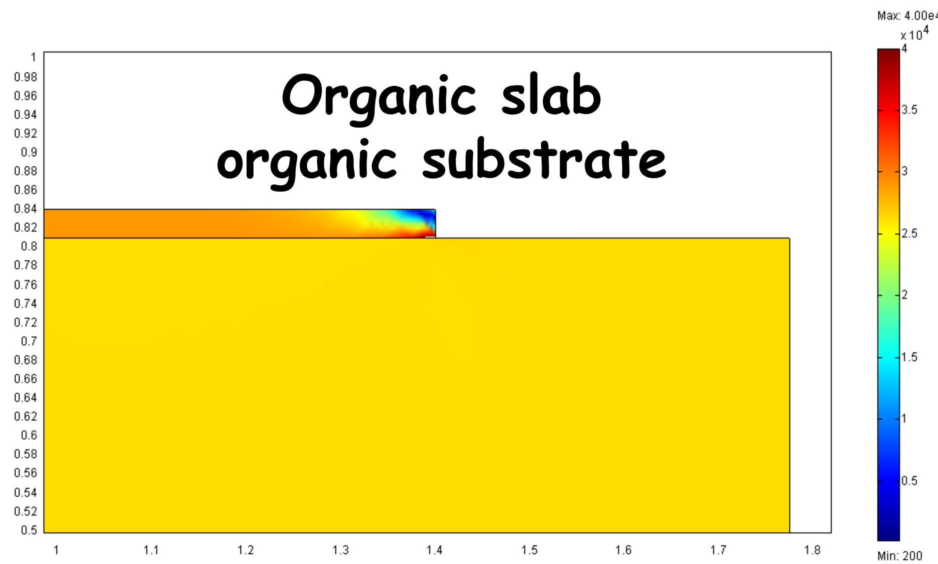
Increasing use and importance of soft materials

Sensors and actuators matched to material can provide performance and reliability advantages

Match Young's modulus, acoustic, thermal characteristics, et cetera

Soft bio-implantable electronics

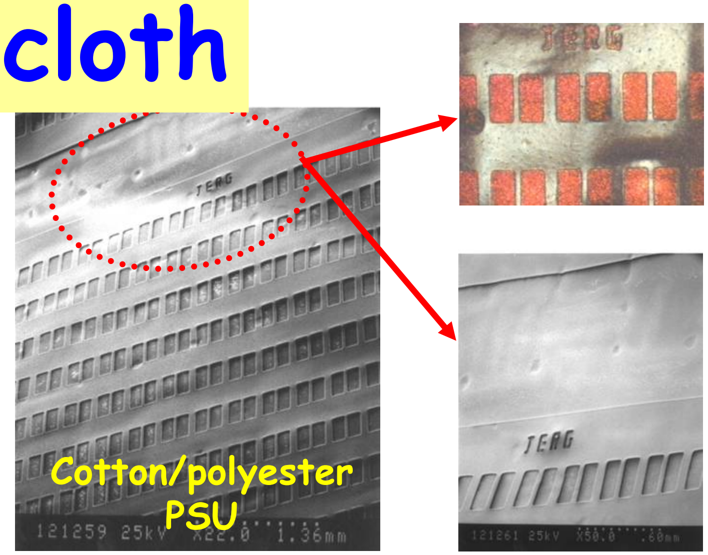




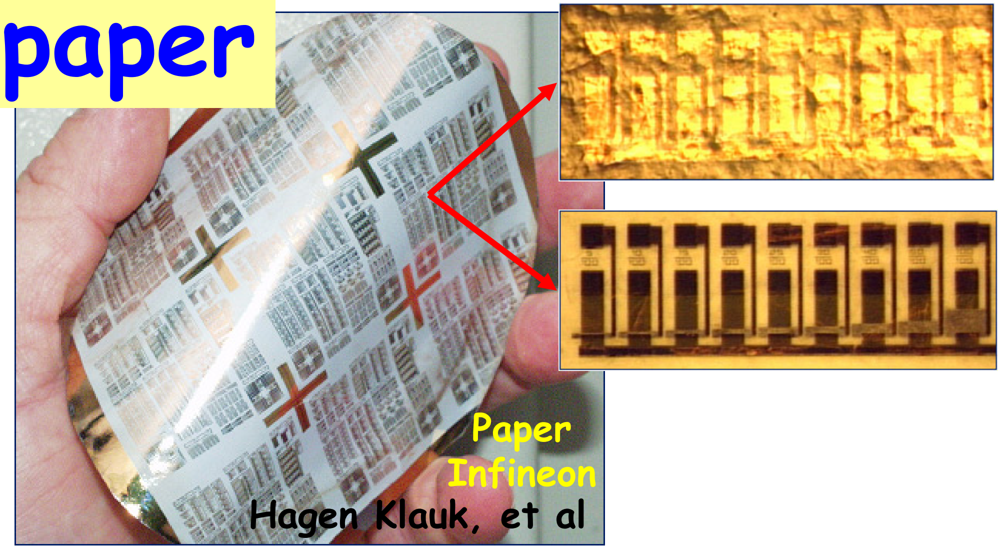
Process Matters

Example: electronics on low temperature materials

cloth



paper



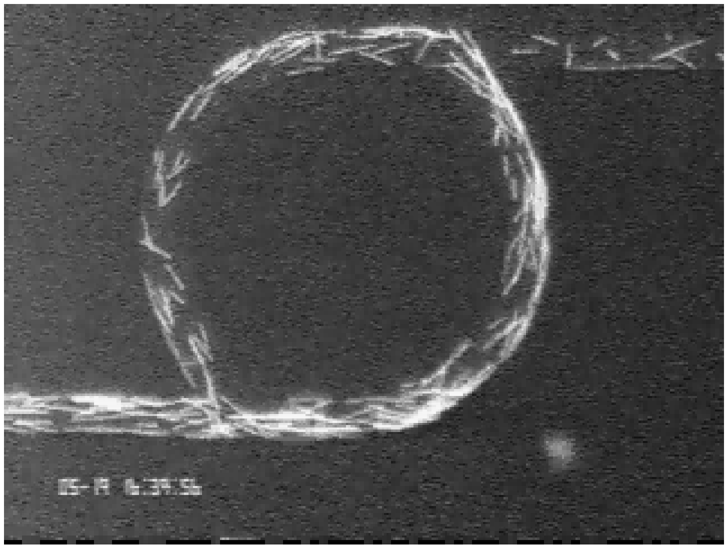
Displays; active camouflage; bio, chemical, radiation, thermal, and health sensors on uniforms

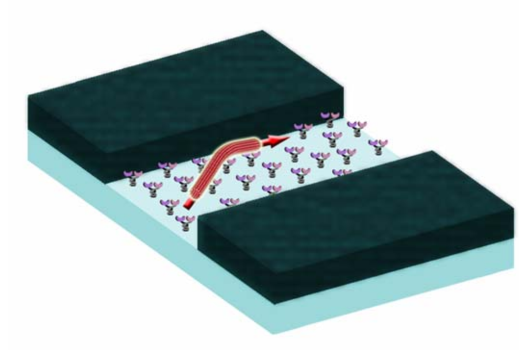
Ultra-low-cost electronics

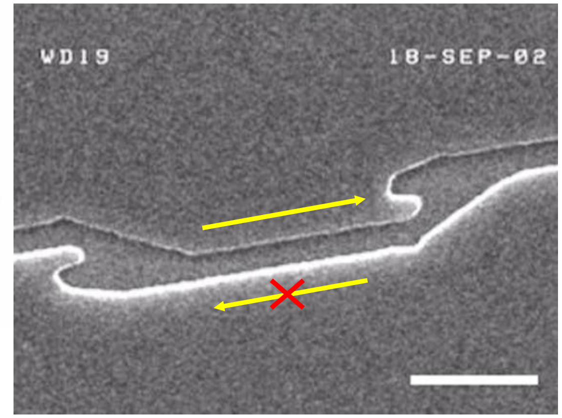
Example: Biophotonics

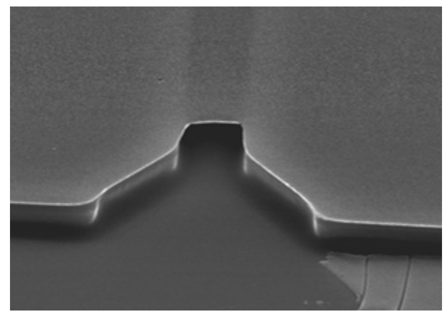
Collaboration with
Will Hancock
PSU Bioengineering

Microtubules move on surface functionalized with kinesin motors







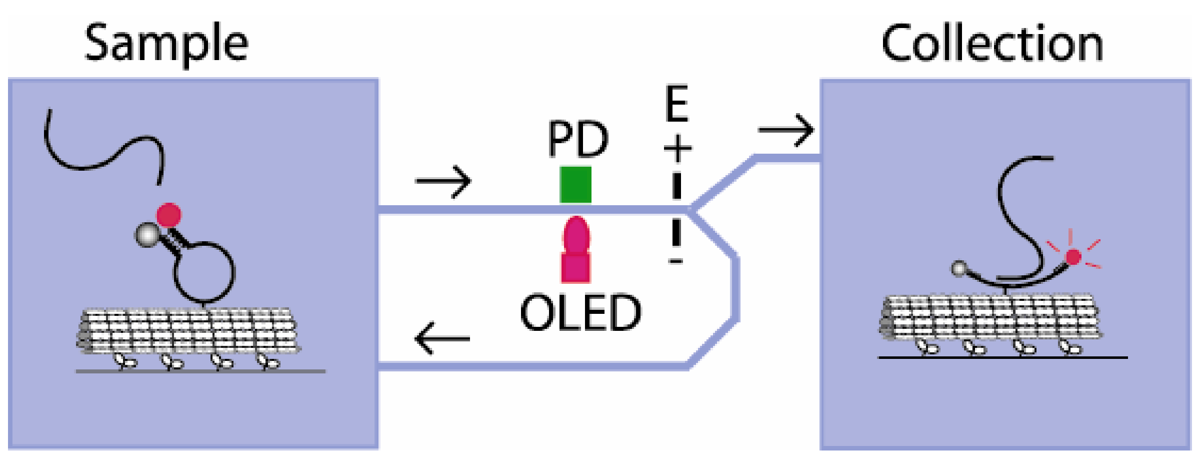


Bio-molecular motors provide simple nanoscale motion – avoid nanofluidic problems

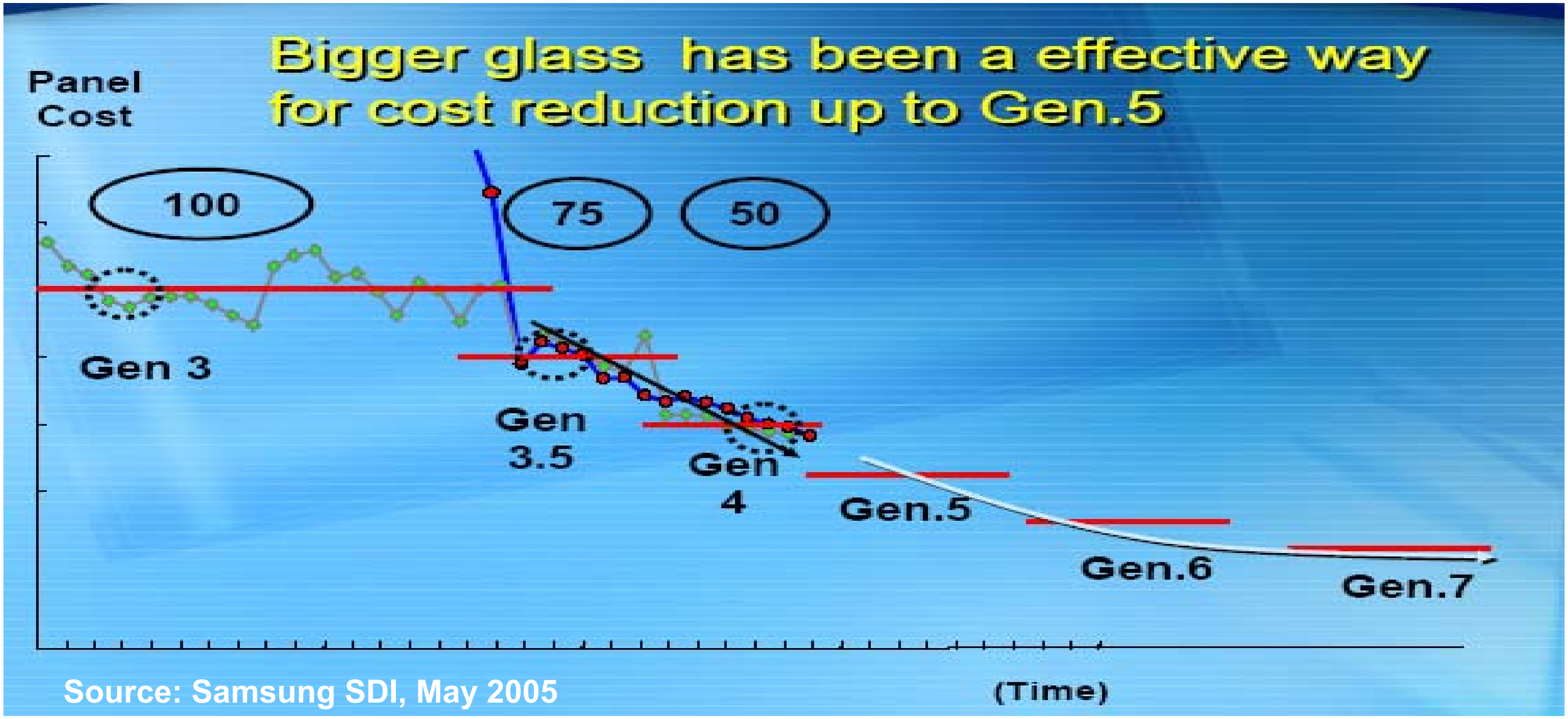
Replace fluorescence microscope with integrated sources and detectors

Organic electronics can provide optical sources, detectors, and control logic

Chemical and biological hazard sensing, micro DNA analysis



Cost Matters



Display manufacturing cost follows car pooling rule

New generation effective way to reduce display cost

Ineffective approach for dramatic cost structure change

Note Gen. 7 plant ~ $\$5 \times 10^9$

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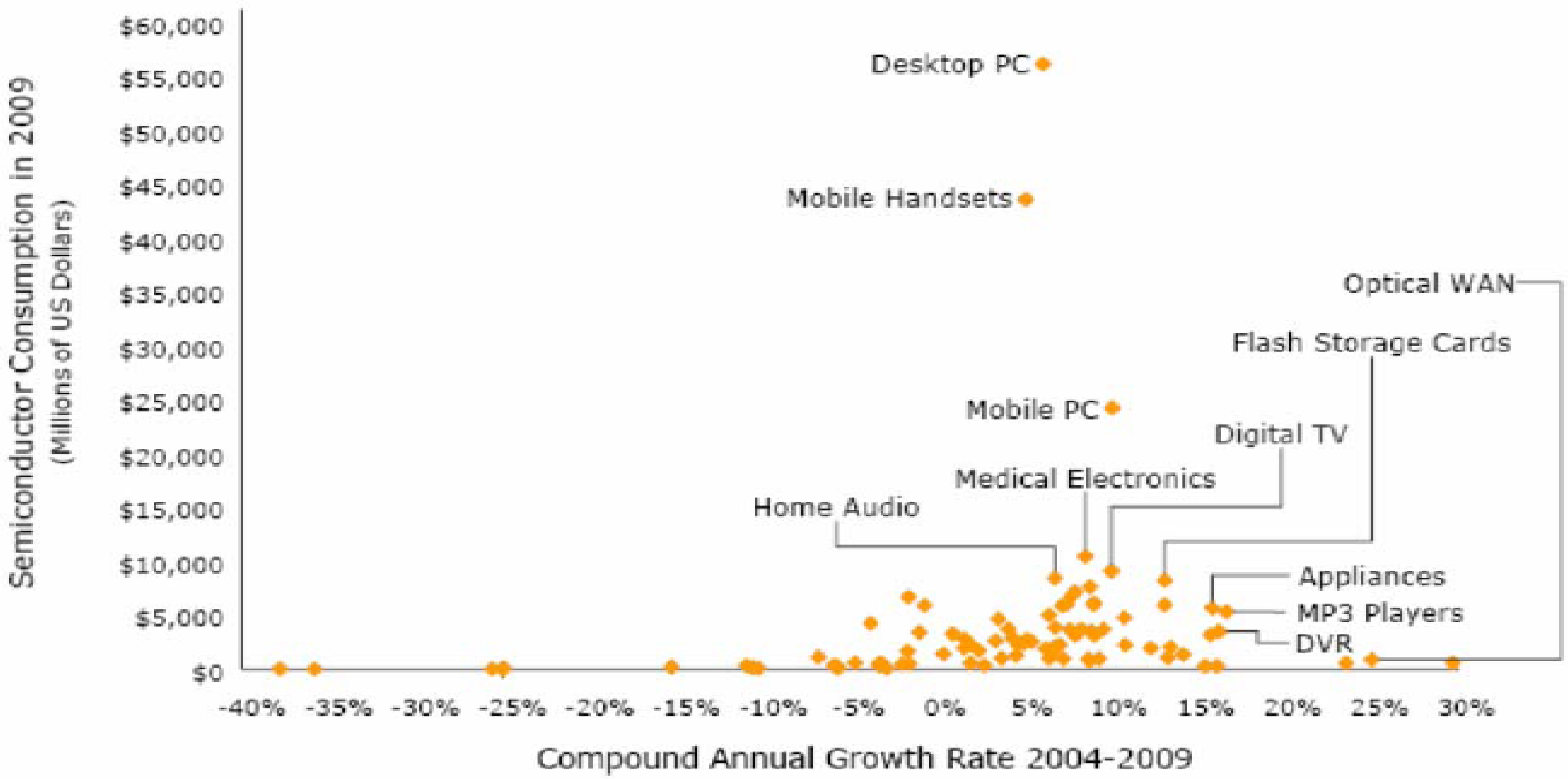
Markets Likely to be Fragmented

More significant problem for large area electronics than for silicon

Semiconductor demand profile

- Other than PCs and handsets, semiconductor demand will be highly fragmented with many markets fading fast...

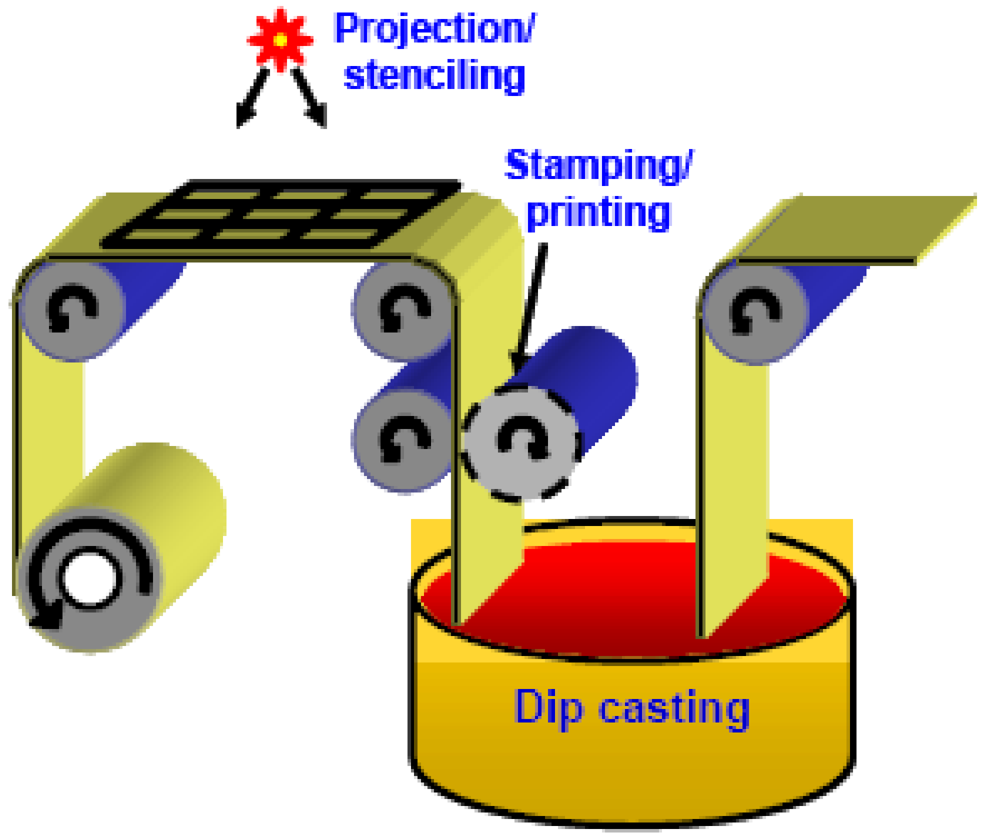


Sources – iSuppli Corporation *Application Market Forecast Tool (AMFT)*™

Cost, Cost, Cost

Opportunity for new processing approaches

- Additive processes
- Low temperature
- Feature size and placement tolerant
- Roll-to-roll process
- High volume production
- Fabrication on arbitrary shape substrates



Cost more important than flexibility

Prediction: Non-Moore's law electronic progress to come will be as stunning as Moore's law progress has been

Electronics Anywhere
-the new frontier-

Baby step:
Flexible Polymeric Substrates

A tale of two substrates

High temperature polyimide – a-Si:H, ZnO

Low temperature polyester – organic TFTs

High temperature polyimide – a-Si:H, ZnO

Evolutionary technology

(build on $\$100 \times 10^9$/year display industry)

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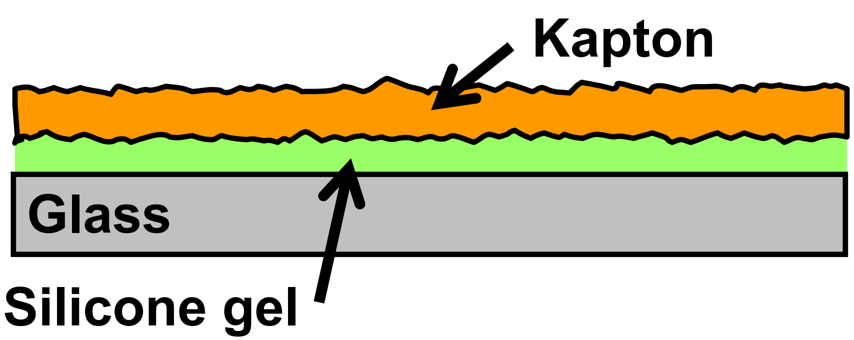
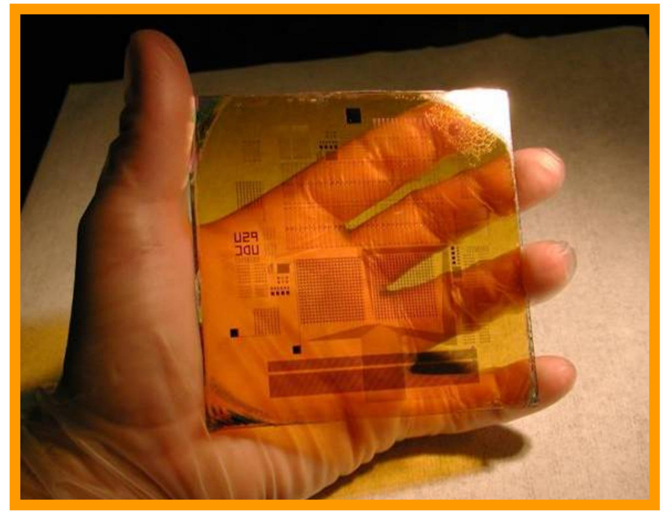
Fabrication on High-Temperature Polymeric Substrates

Hydrogenated amorphous silicon thin film transistor fabrication

- Polyimide substrates
  - Good thermal and chemical stability

  $\Rightarrow$ treat just like glass
- Substrate laminated to glass carrier with pressure-sensitive silicone gel
- Maximum process temperature = 250 °C





Differential-pressure vacuum laminator

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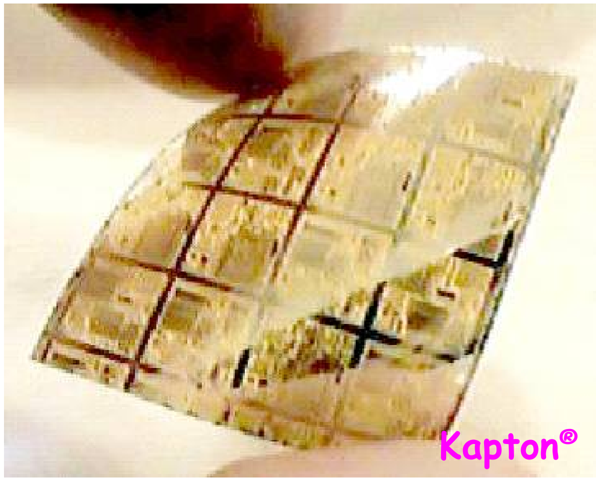
a-Si:H TFT-based Sensors and Circuits

Large area sensors, actuators, displays, et cetera, on arbitrary substrates

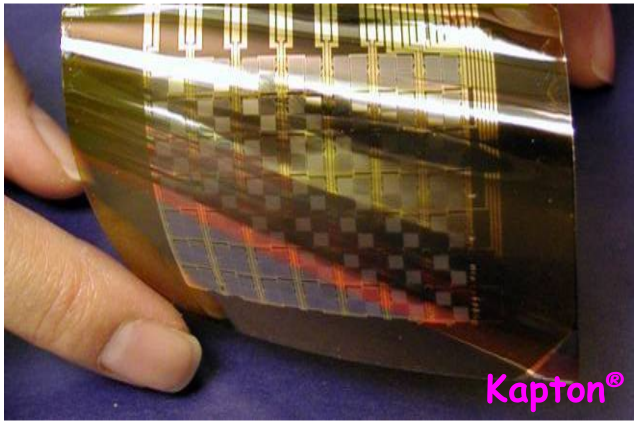
Bring microelectronics to the function

a-Si:H ICs

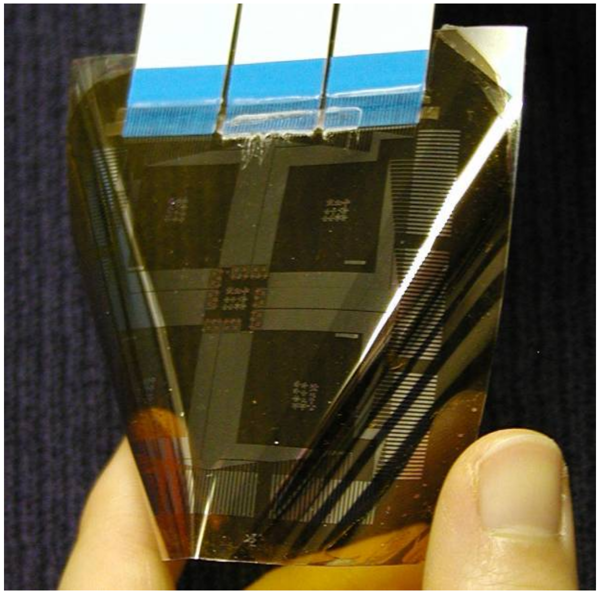


a-Si:H photovoltaics

a-Si:H strain bridge array

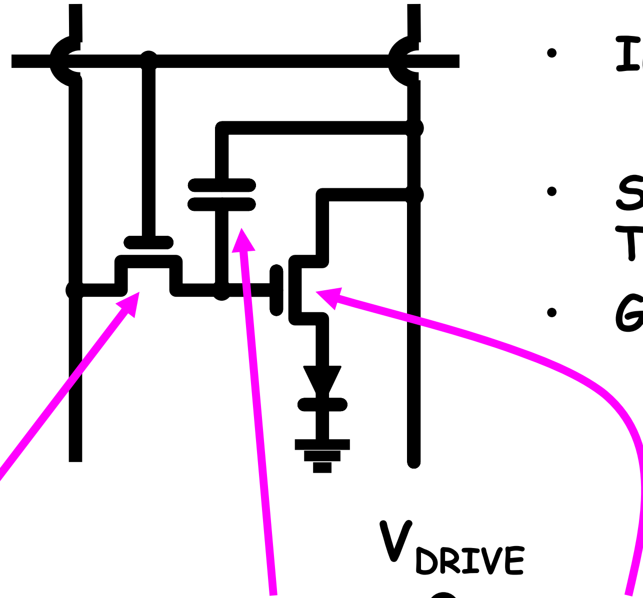


a-Si:H gamma ray detector

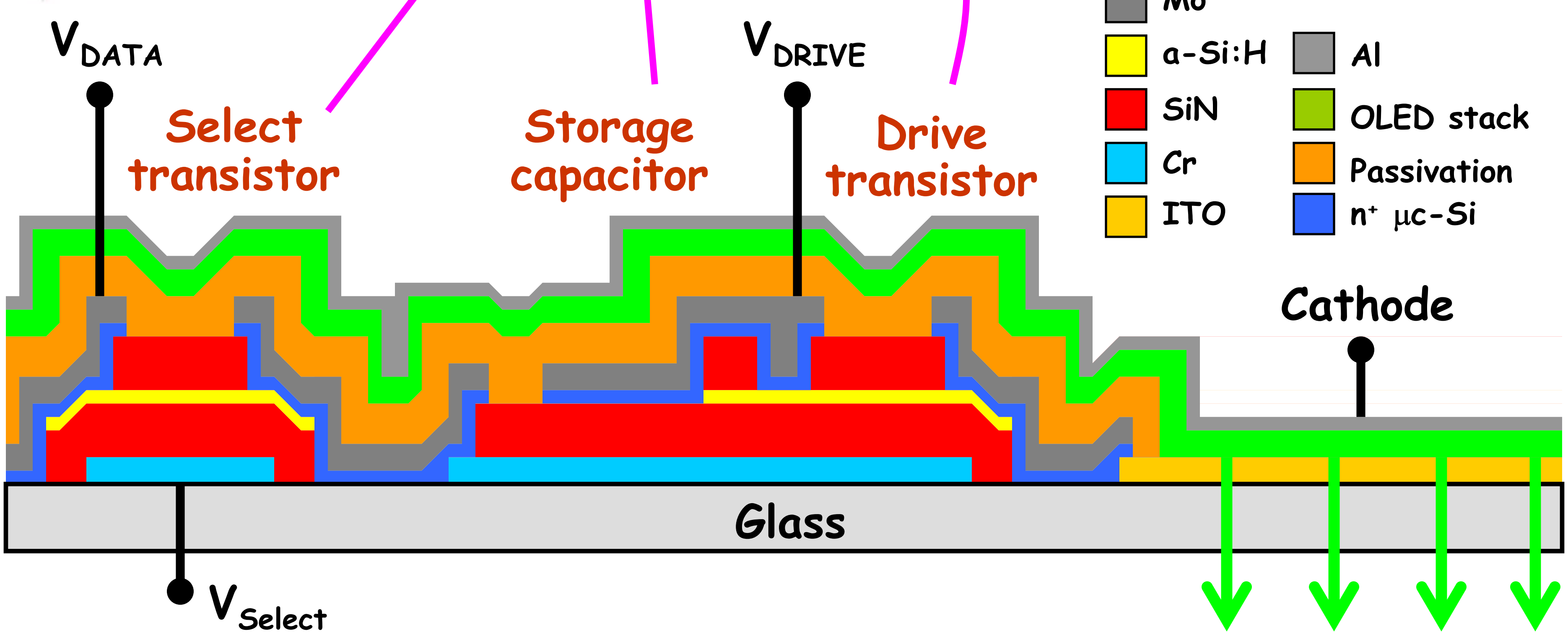


μC-Si strain sensors

a-Si:H TFT Active Matrix OLED Pixel



- Inverted staggered tri-layer a-Si:H TFT process
- Silicon nitride layer isolates TFTs and OLEDs
- Green emitting OLEDs



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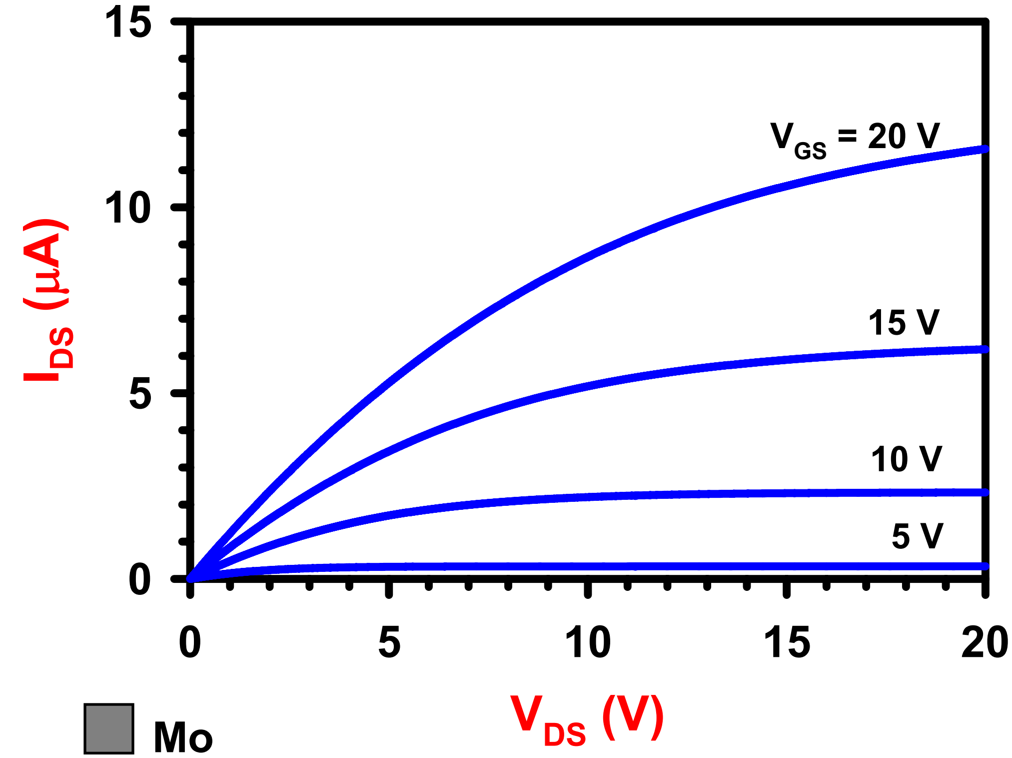
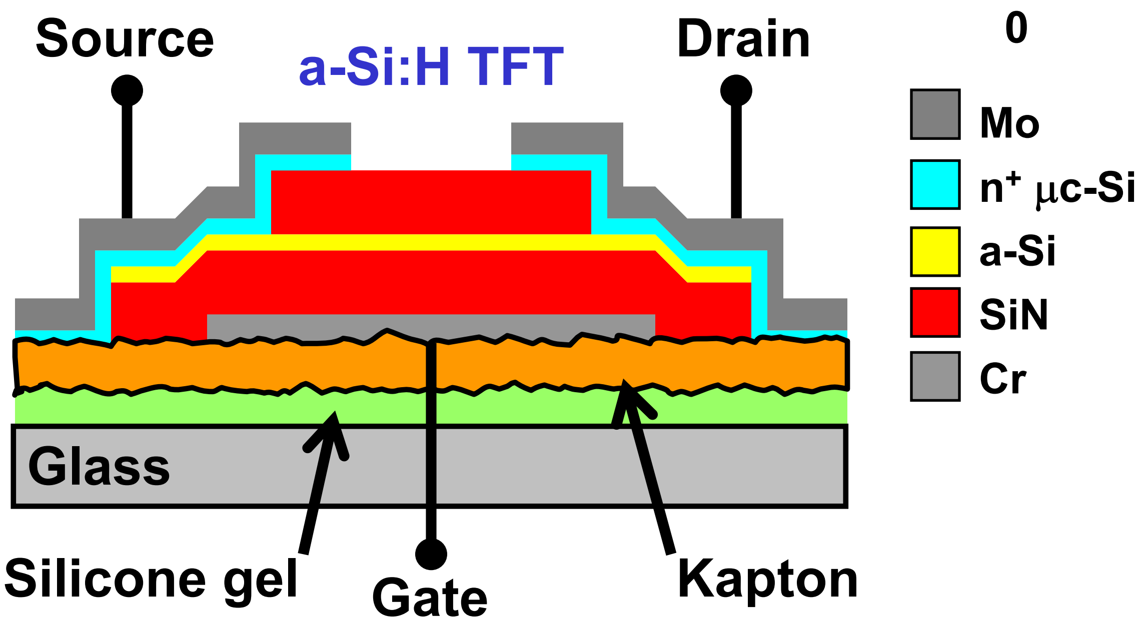
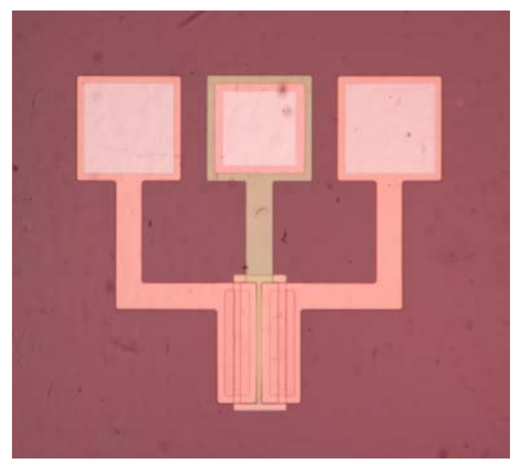
a-Si:H TFT AMOLED Pixel – Polyimide Substrate

UNIVERSAL DISPLAY CORPORATION

- TFT Performance similar to TFTs fabricated on glass
  - Mobility = 0.8 cm²/V-s
  - Threshold voltage = 1.6 V
  - Sub-threshold slope = 0.5 V/decade







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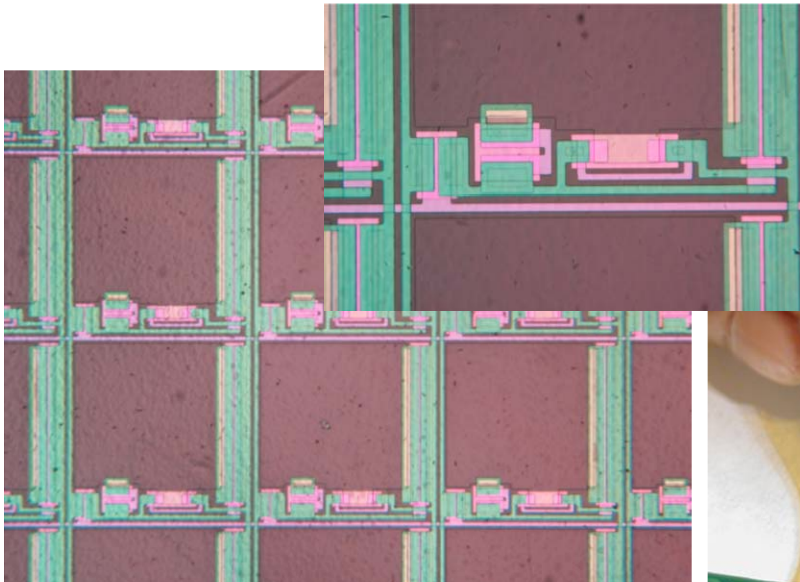
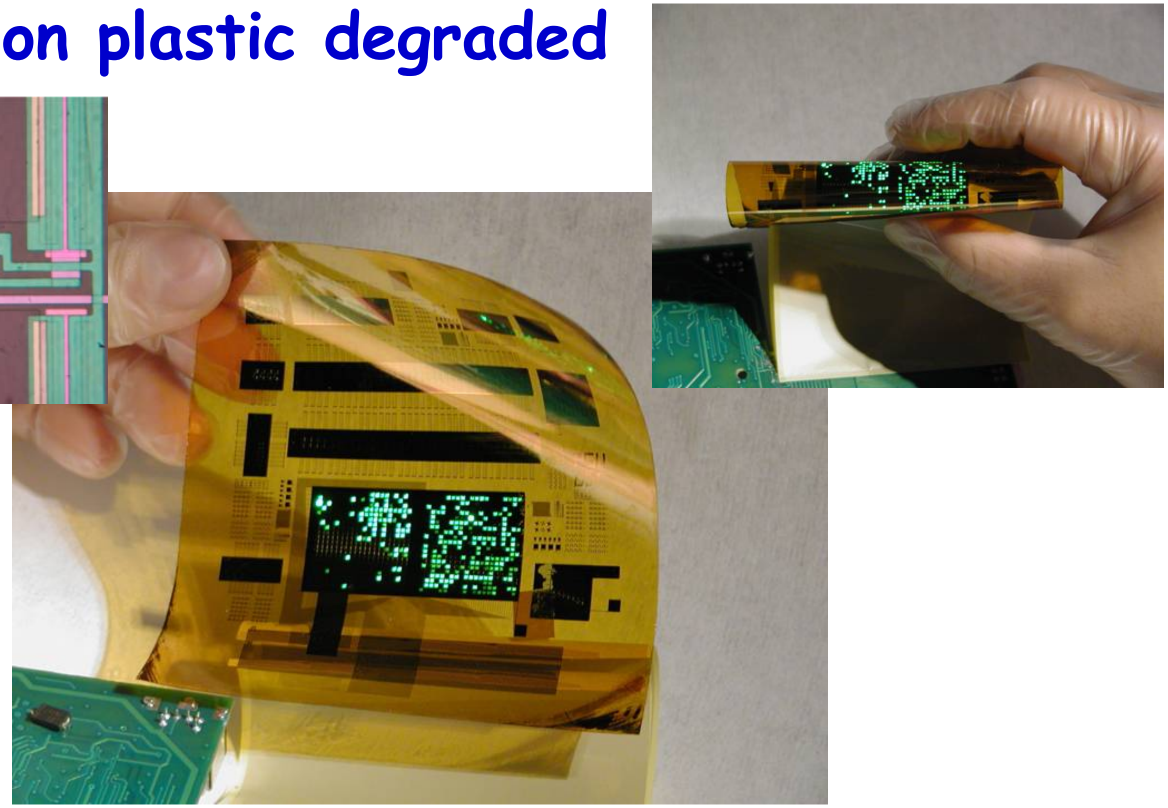
a-Si:H TFT AMOLED Pixel – Polyimide Substrate

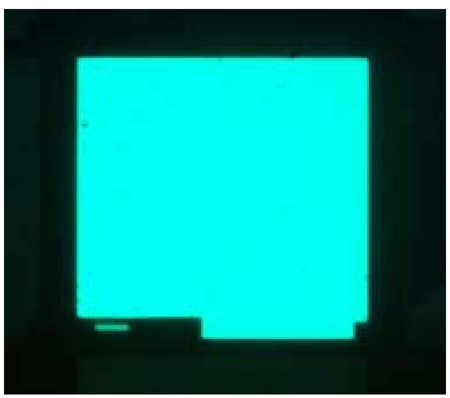
UNIVERSAL DISPLAY CORPORATION

OLED pixels on plastic degraded

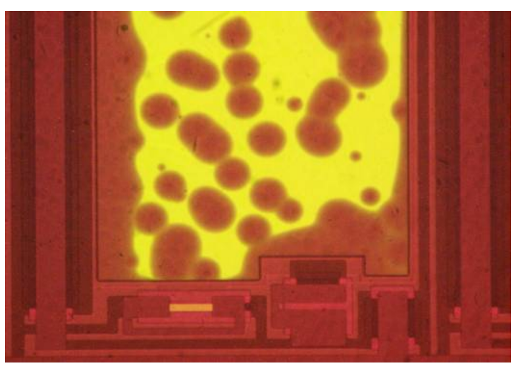


Pixel Array

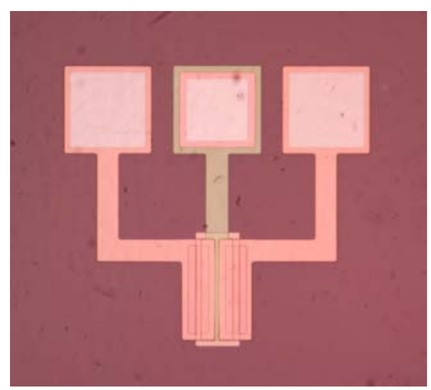




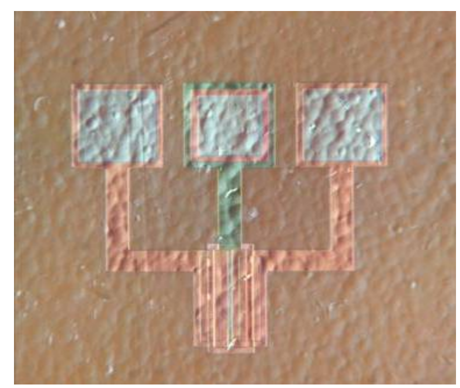
Pixel on Glass



Pixel on Polyimide

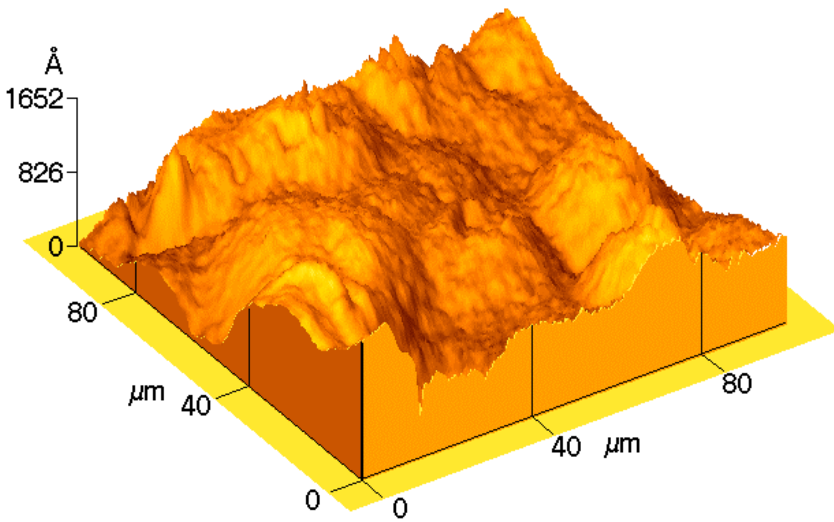


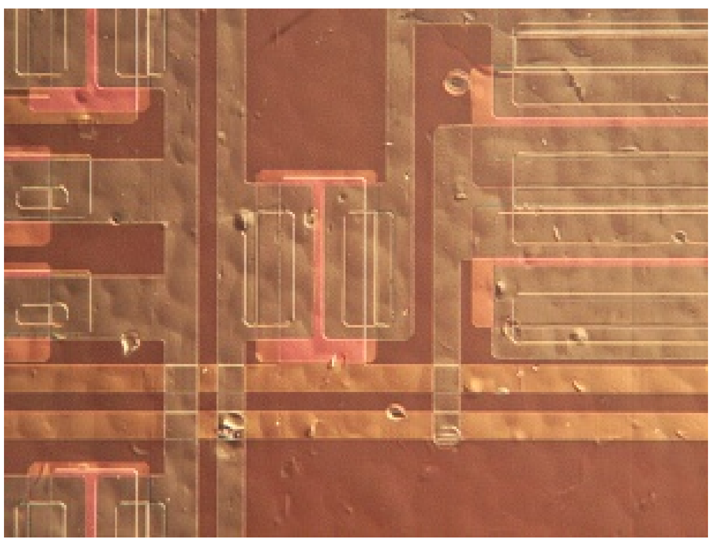
Bright field



DIC

Polyimide Surface Roughness





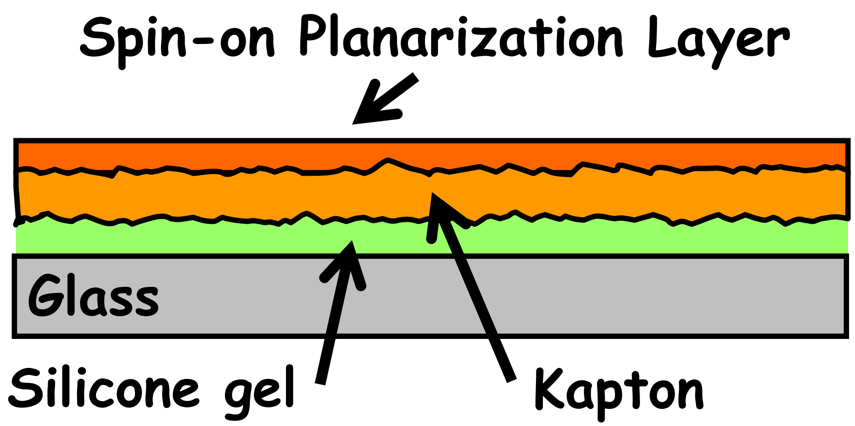
~ 30 nm RMS roughness over small areas

"Rolling hills" topography

Can make heat transfer problematic; solved by silicone gel mountant

But surface also has sparse, sharp, high relief features (also easy to add features)

- Planarization?



- Chemical-mechanical polishing?

Low Temperature Polymer Substrates

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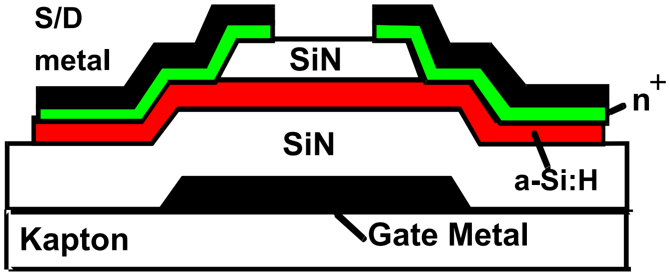
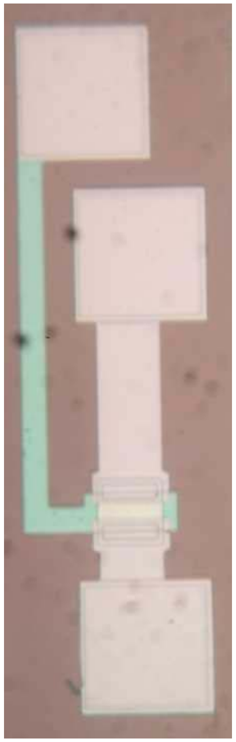
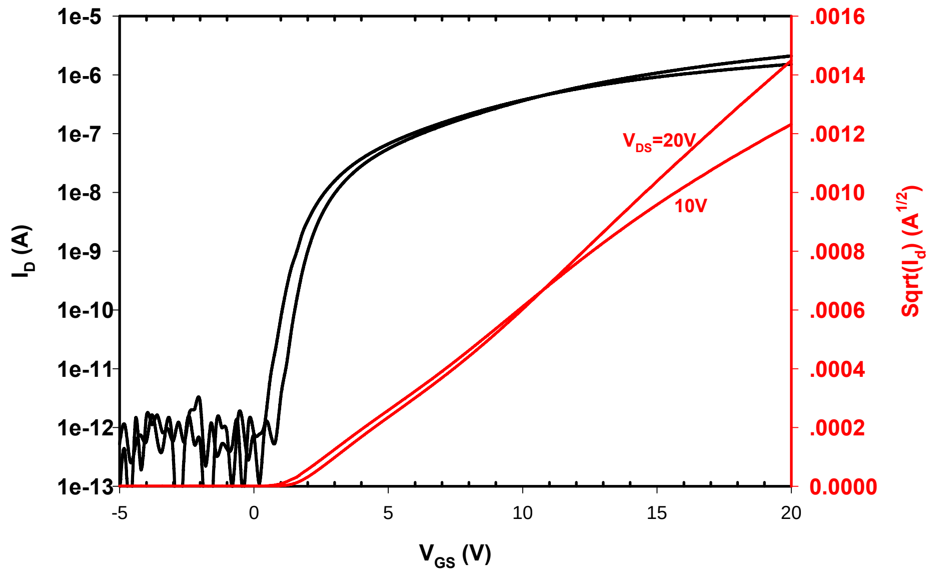
a-Si:H TFTs fabricated with H_2 dilution at 150 °C





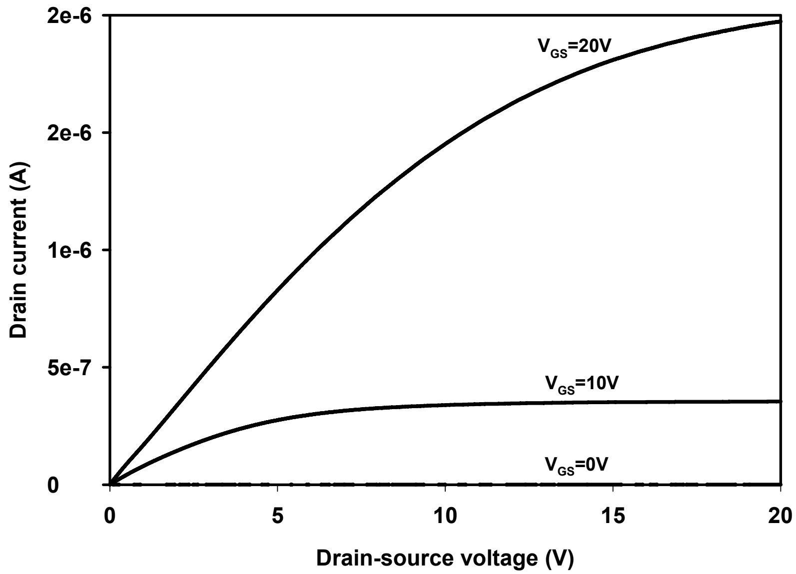


Saturation mobility
$1.0\ cm^2/Vs\ @V_{DS}=20V$

Linear mobililty
$0.7\ cm^2/Vs$

Threshold voltage
3.2 V

Sub-threshold slope
0.4 V/Dec

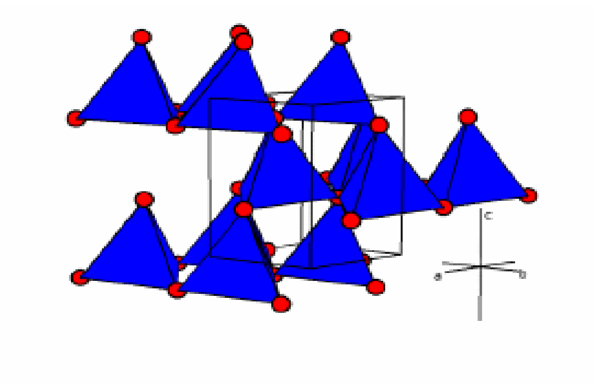


Doped and Undoped ZnO

Deposition temperature 180 – 200 °C, possibly lower

Doped film resistivity as low as 3×10^{-4} Ω-cm

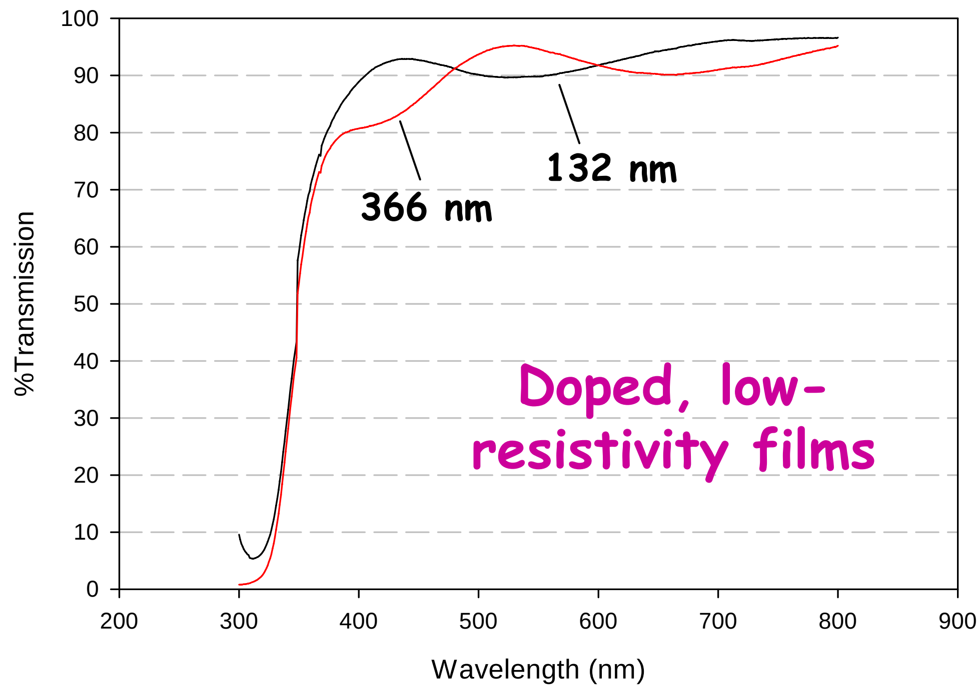
Doped film electron mobility ~ 10 cm^2/V-s, undoped higher



ZnO
Wurtzite ($P6_3mc$)
4-coordinate Zn^{2+}
4-coordinate O^{2-}
Corner Sharing

Good transparency

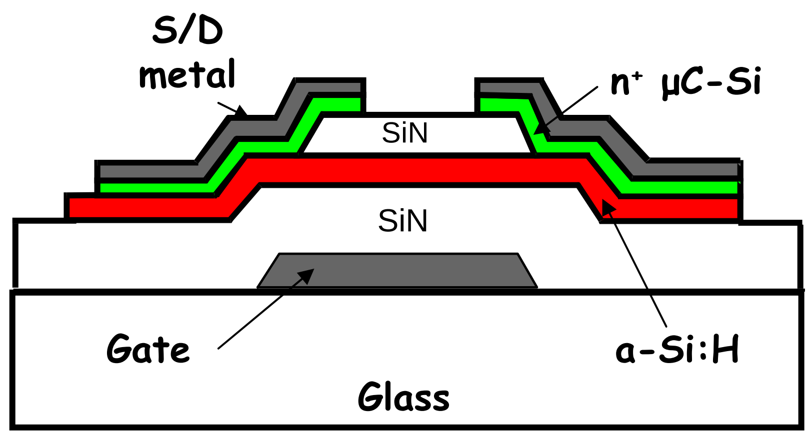
Optical transmission

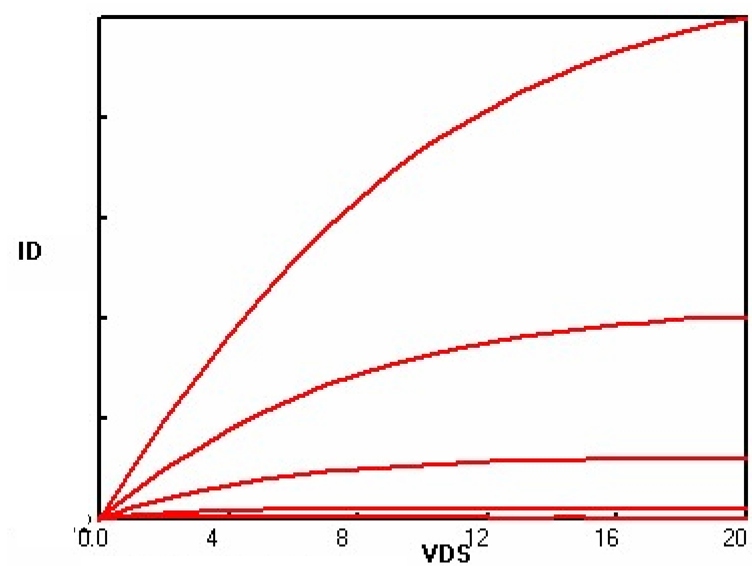


ZnO TFTs

Most ZnO TFTs demonstrated to date have not used contact doping

Hoffman, et al
APL 86, 13503 (2005)





Doped contacts likely to improve TFT extrinsic mobility and off current

Low temperature polyester – organic TFTs

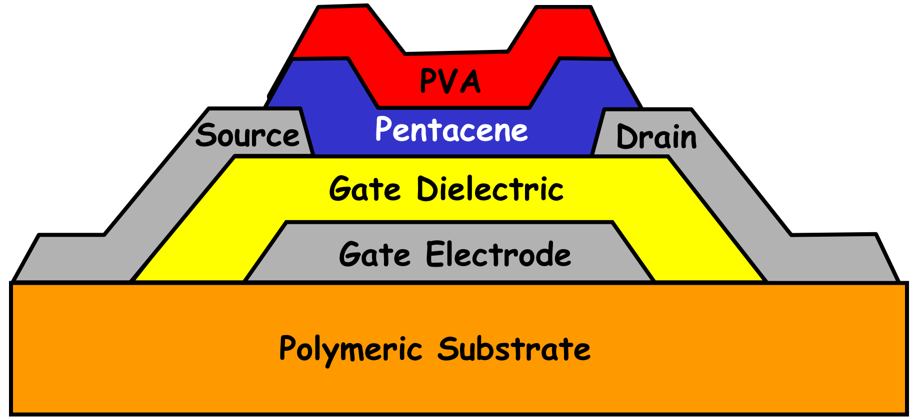
Revolutionary technology

(some connections to $3 × 10^9/year OLED "industry")

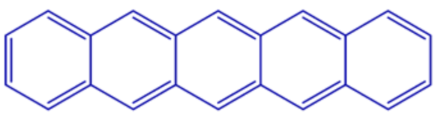
Small Molecule Organic Semiconductors

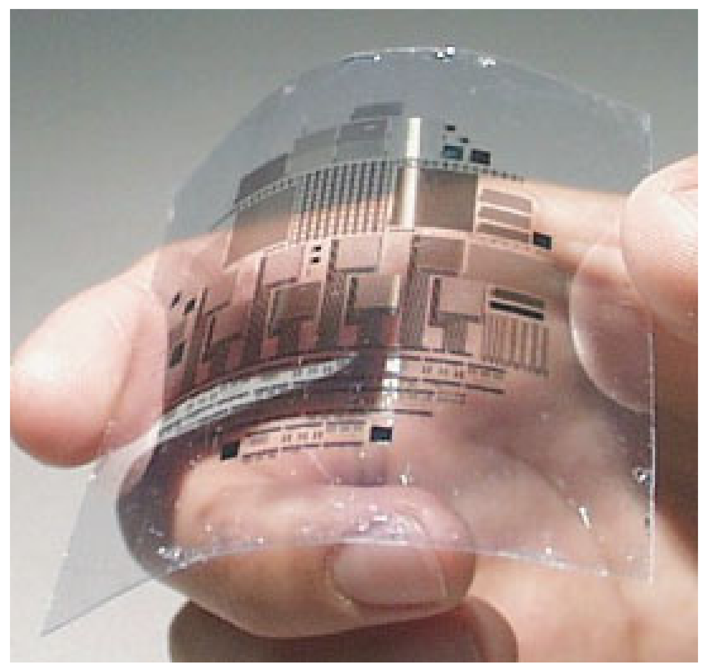
- Low temperature processing allows arbitrary substrates and flexible processing

- Simple device fabrication



Pentacene:

-  pentacene



- Small molecule organic semiconductor
- Thin film mobility > 3 cm^2/V-s, ~ 1 cm^2/V-s typical
- Simple low-temperature vacuum deposition
- Strong tendency to form well-ordered molecular crystals

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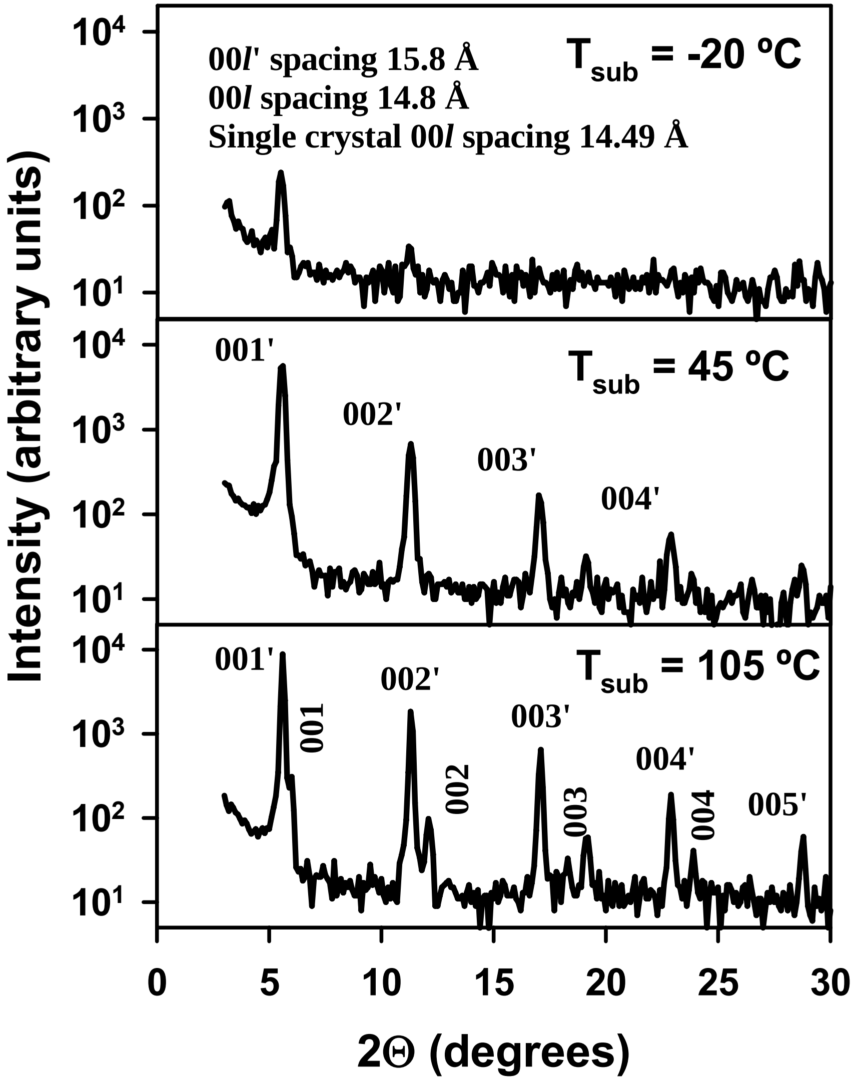
Molecular Crystals

- **Molecular self-assembly**
- **Films ordered at low temperature**
- **Islands of electron density**

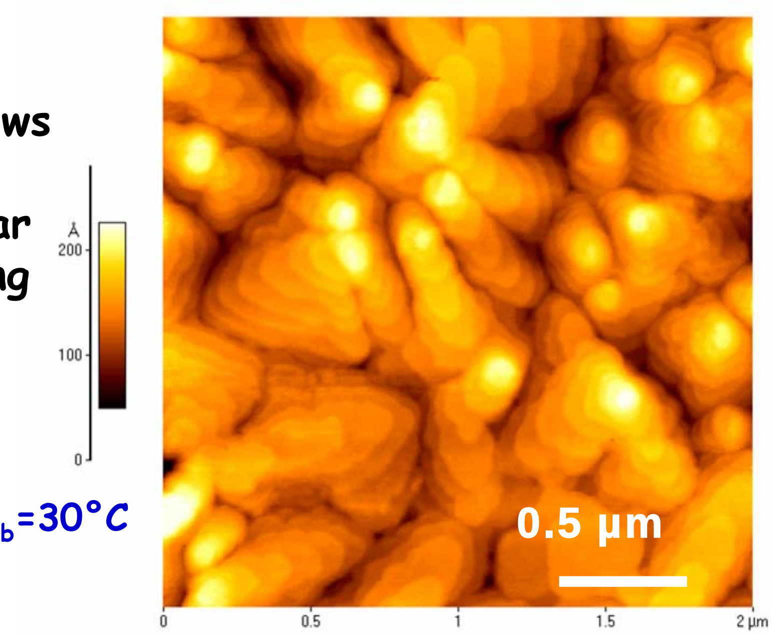
x-ray diffraction

500 Å Pentacene films



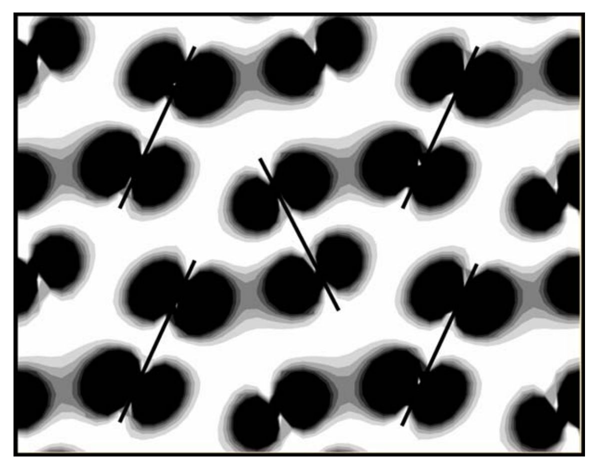
AFM shows strong molecular terracing

T_{sub}=30°C



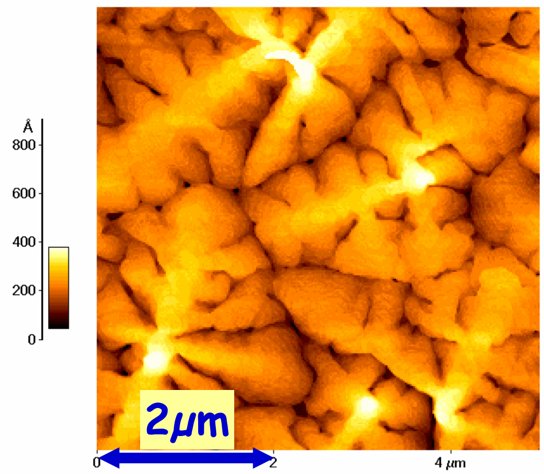
Homo electron density, looking along c-axis

(K. Hummer, P. Puschnig, C. Ambrosch-Draxl *Electronic Properties of Oligo-Acenes*, April 2003, Vienna, Austria)

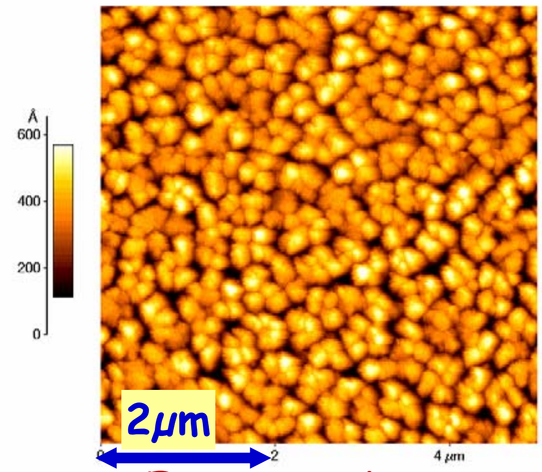


Small-Molecule Organic Semiconductor Growth

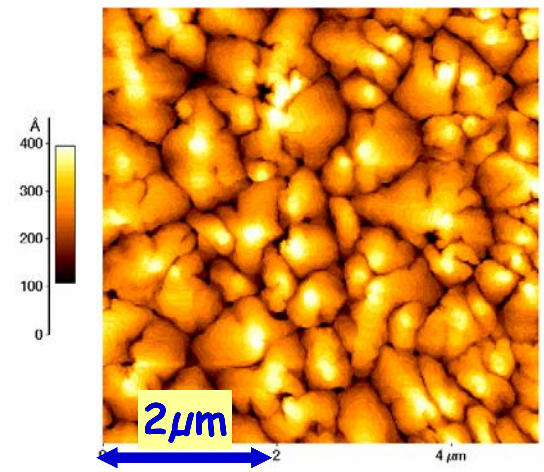
Surface roughness



Thermal SiO_2
~ 1 Å rms roughness



Evaporated Au
~ 5 Å rms roughness

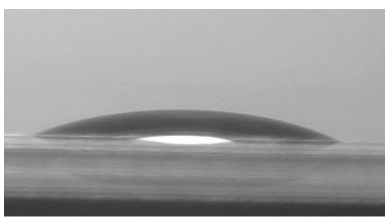


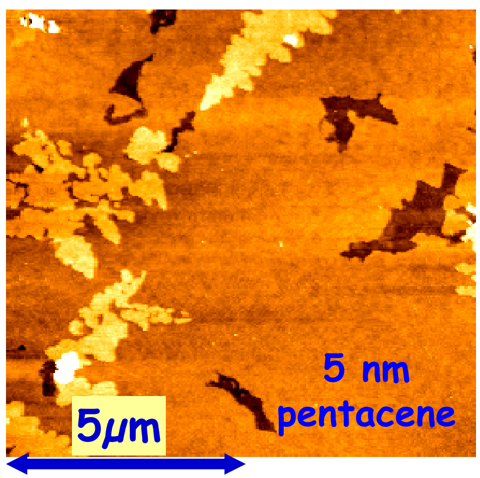
Ion beam sputtered Pd
~ 2 Å rms roughness

Surface energy

untreated SiO_2

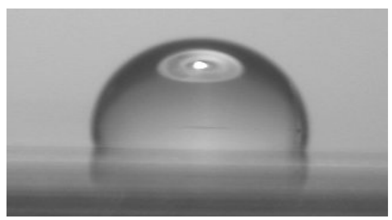
high surface energy

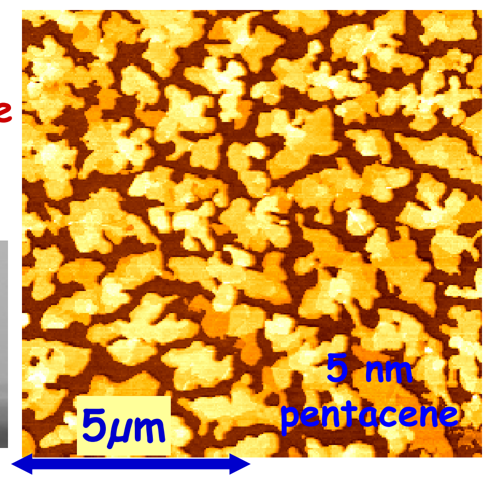




SiO_2 treated with octadecyltrichlorosilane (OTS)

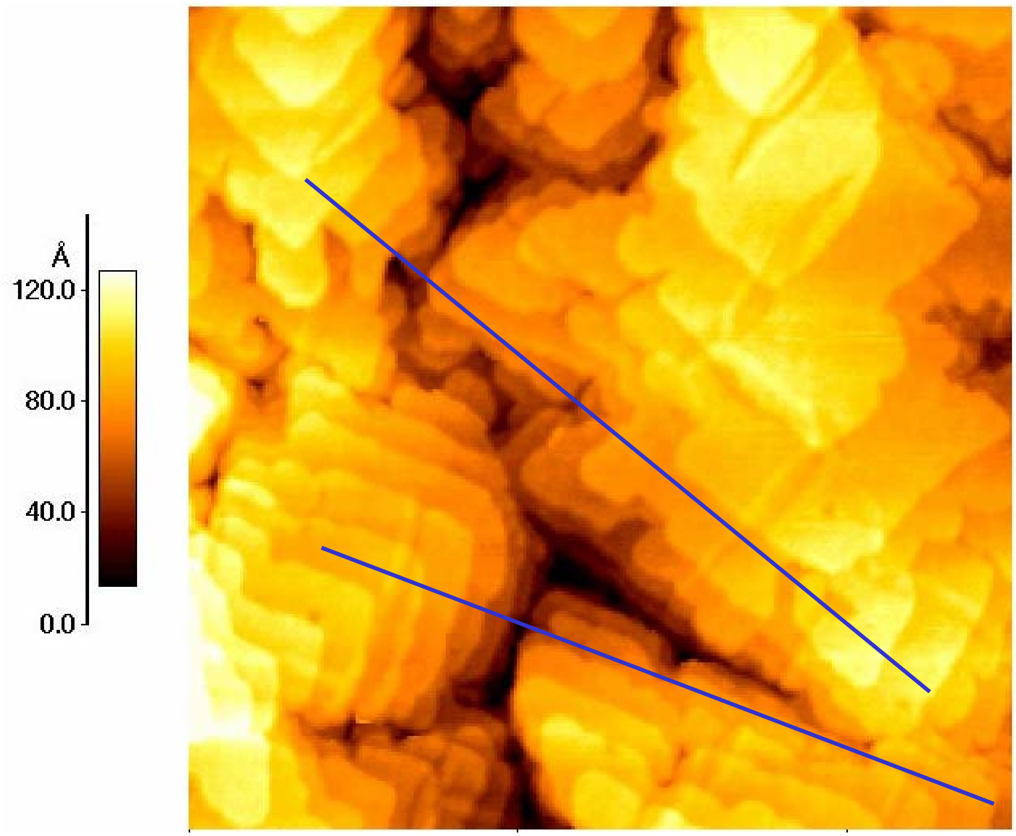
low surface energy





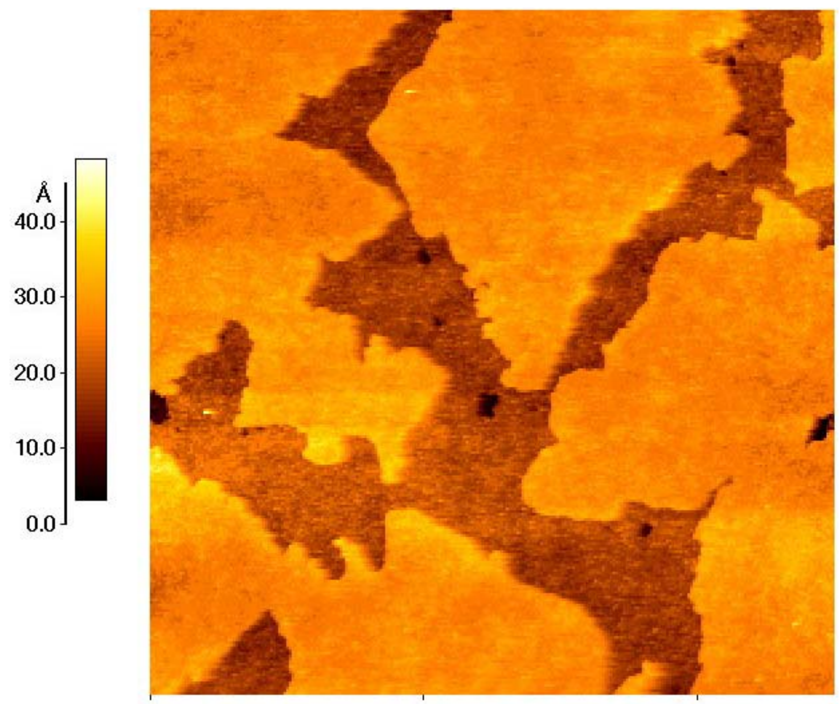
Organic Semiconductor Grain Boundaries?

Facet directions are often coherent across apparent grain boundaries



30 nm average thickness

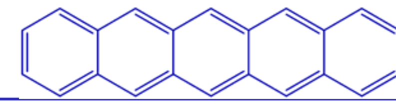
Connection of topography to microstructure and transport not clear



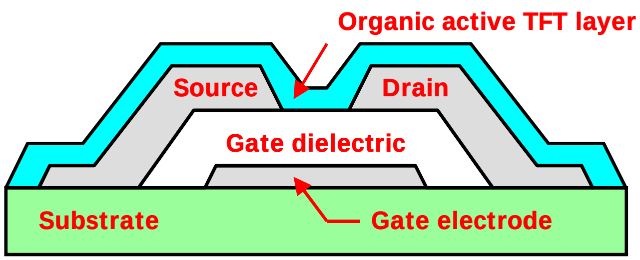
5 nm average thickness

No clear correlation between grain boundary density and OTFT performance

Pentacene OTFTs

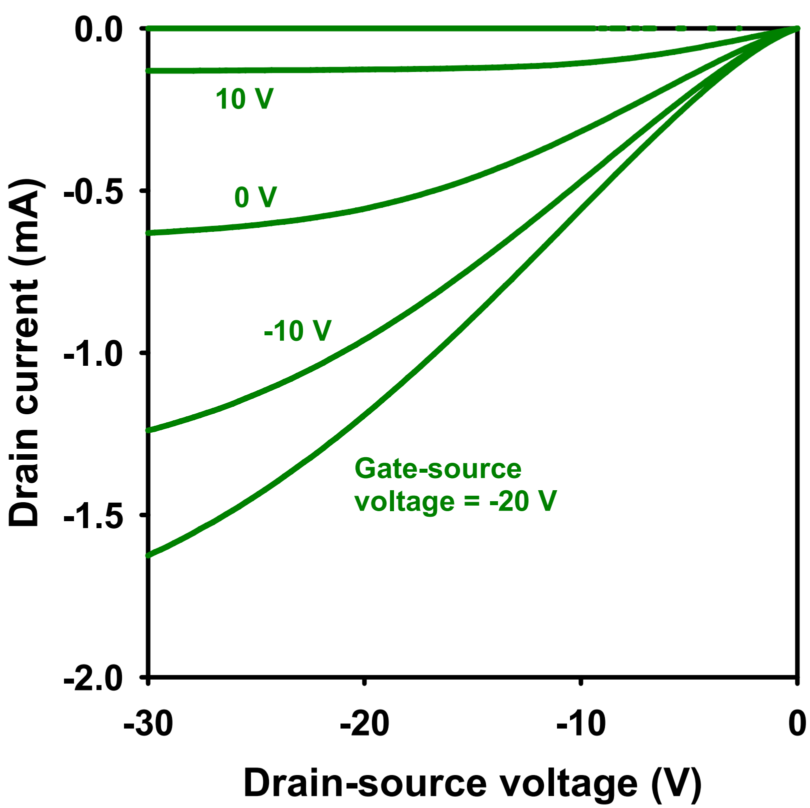


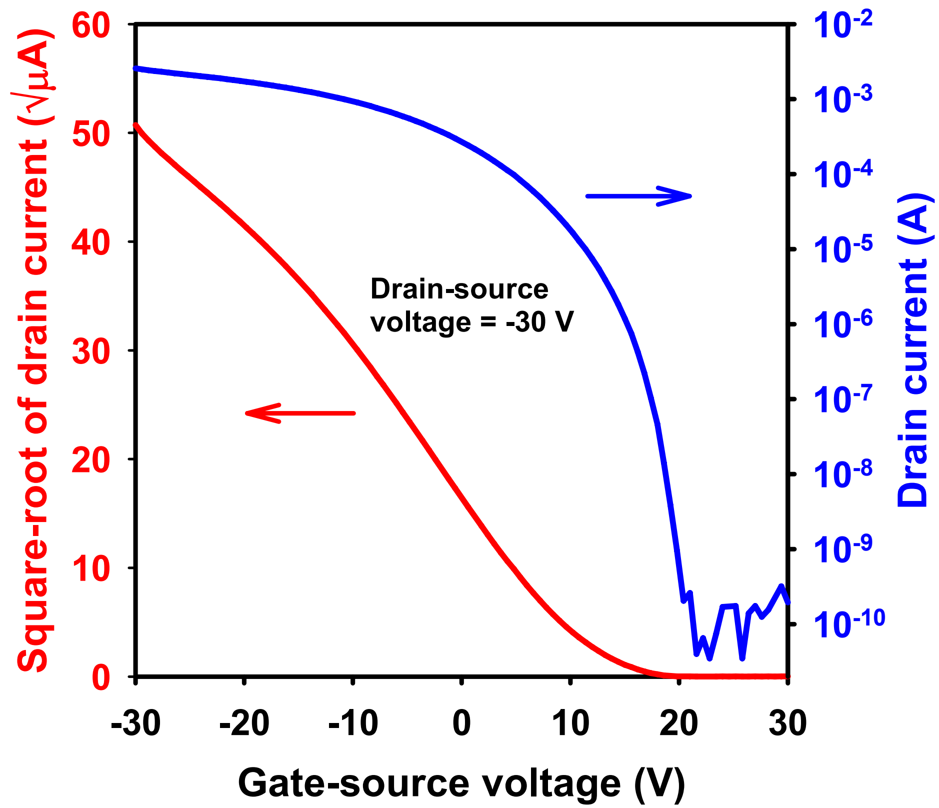
Hard substrate (glass or silicon) devices



$W / L = 500\ \mu m / 5\ \mu m$, $t_{ox} = 150$ nm

$\mu = 1.7\ cm^2/V\text{-}s$, $I_{on} / I_{off} = 10^8$, $S = 0.9$ V/dec





Polymeric Substrate OTFT Process

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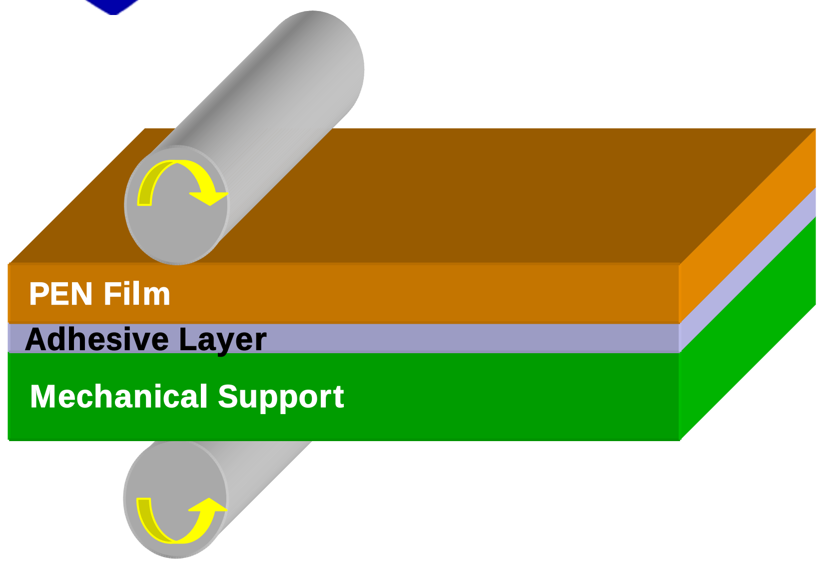
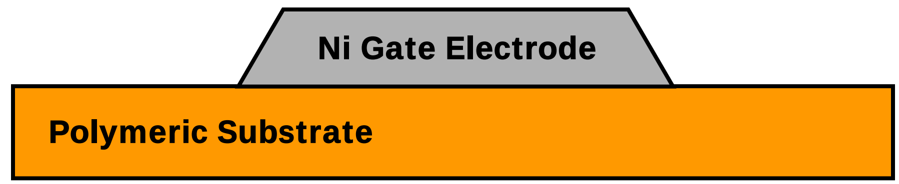
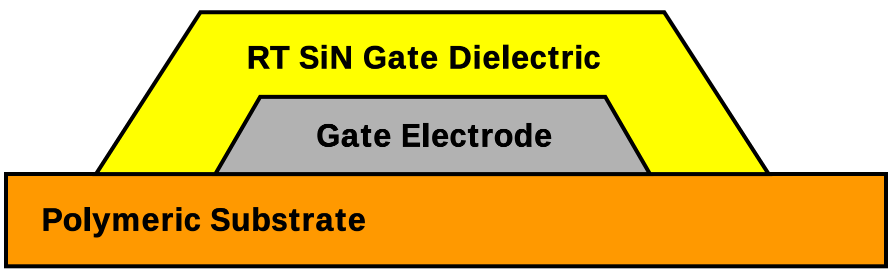


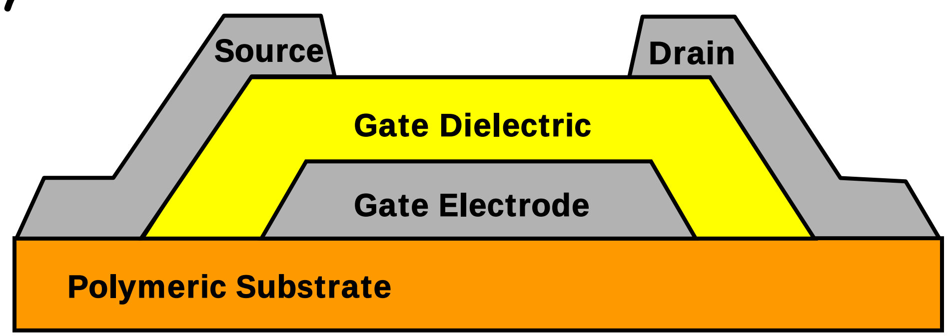
Polymeric film mounted to support,
preshrink to improve thermal stability



Ni gate electrode
deposited and patterned

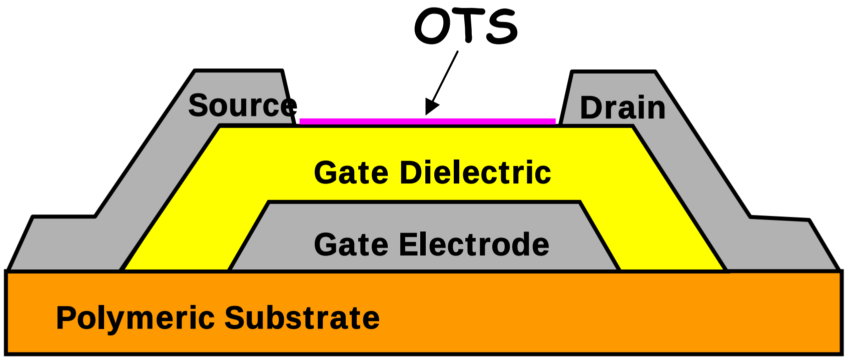


Room-temperature PECVD
SiN deposited and patterned

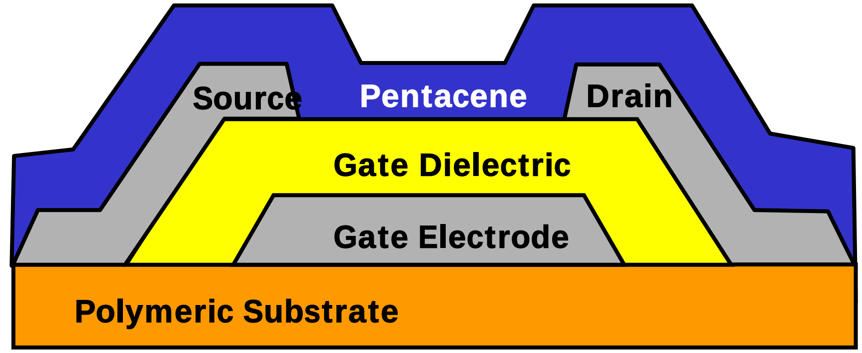


Pd source and drain electrodes
deposited and patterned

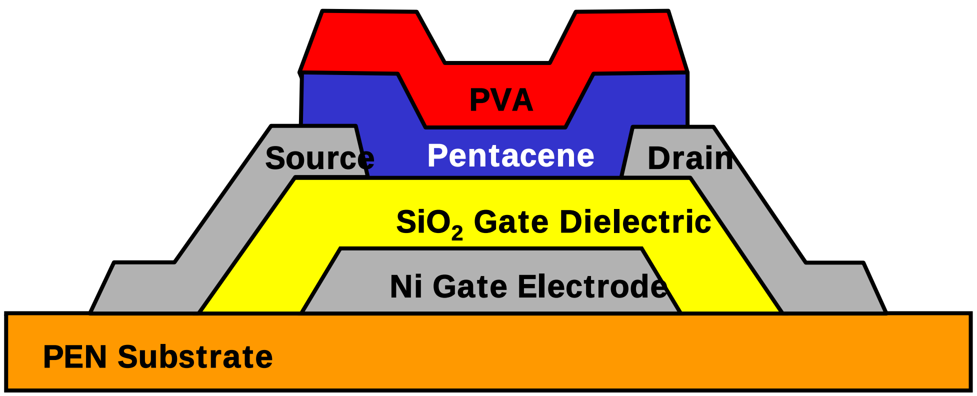
Polymeric Substrate OTFT Process



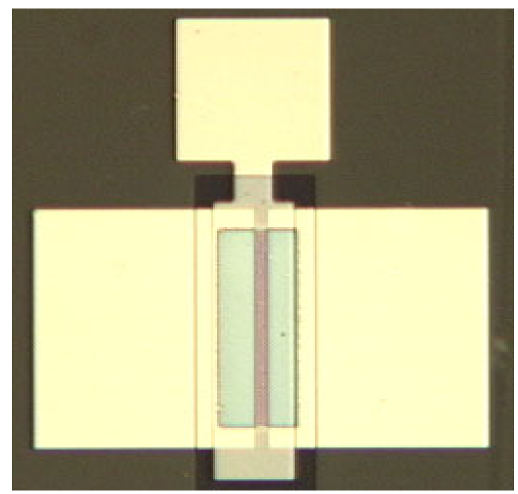
SCA (octadecyltrichorosilane) treatment



Pentacene active layer deposited



Pentacene patterned using water-based photoresist and plasma etching



Completed discrete device

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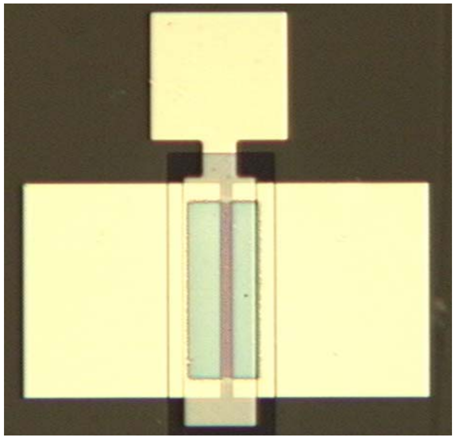
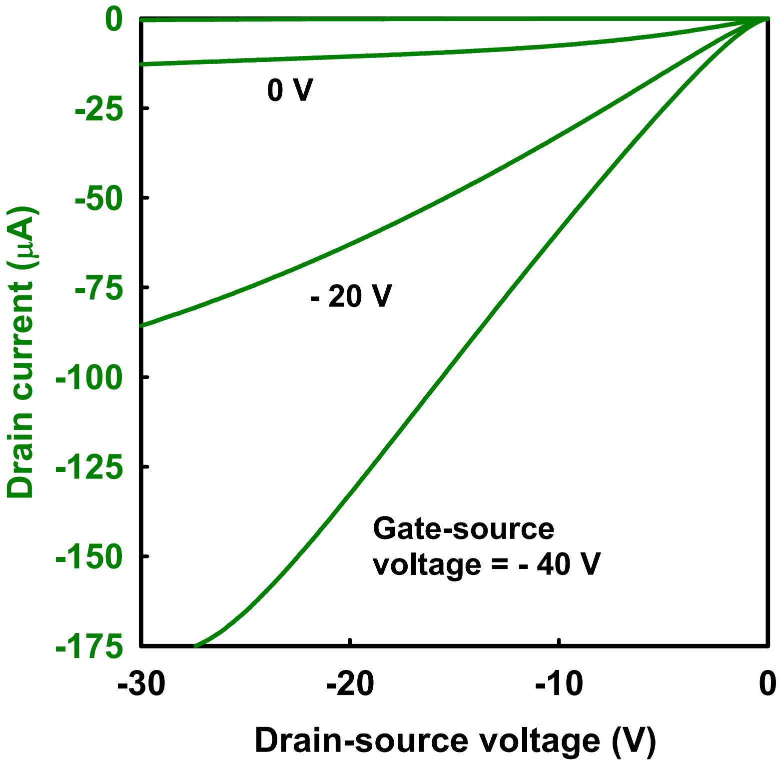
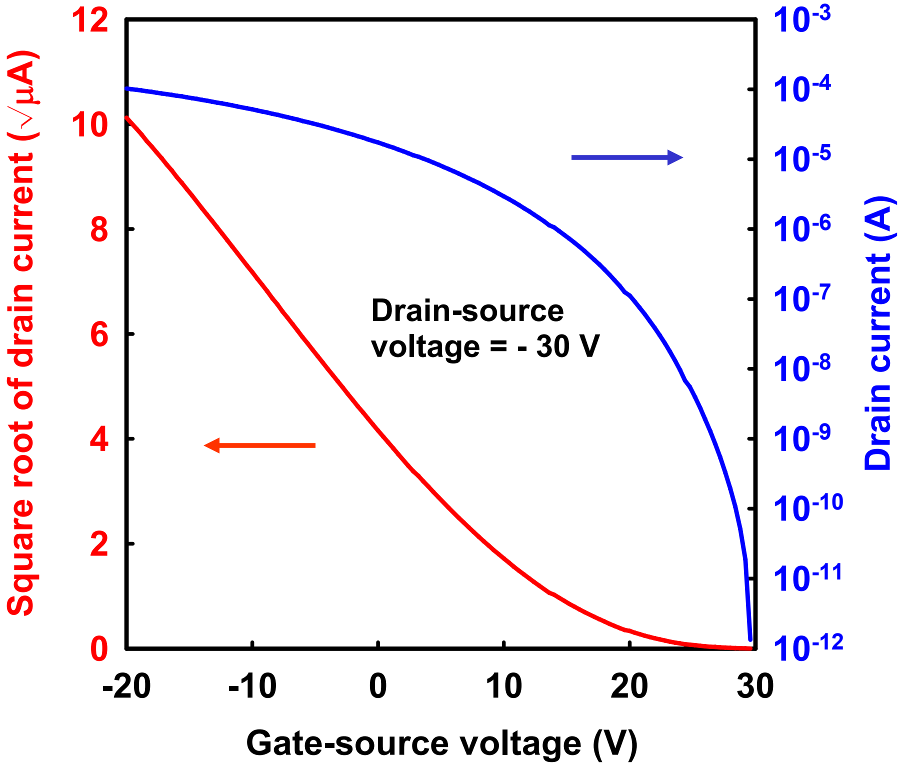
Pentacene OTFTs on Polymeric Substrates

Discrete TFT Characteristics



W / L = 200 μm / 10 μm, t_{ox} = 450 nm
μ = 1.2 cm^2/V-s, I_{on} / I_{off} = 10^8

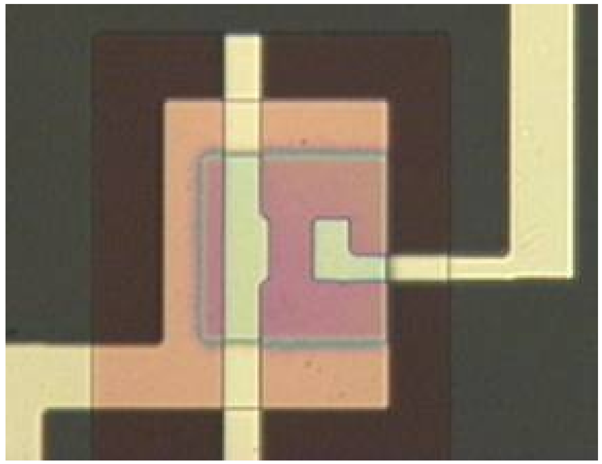


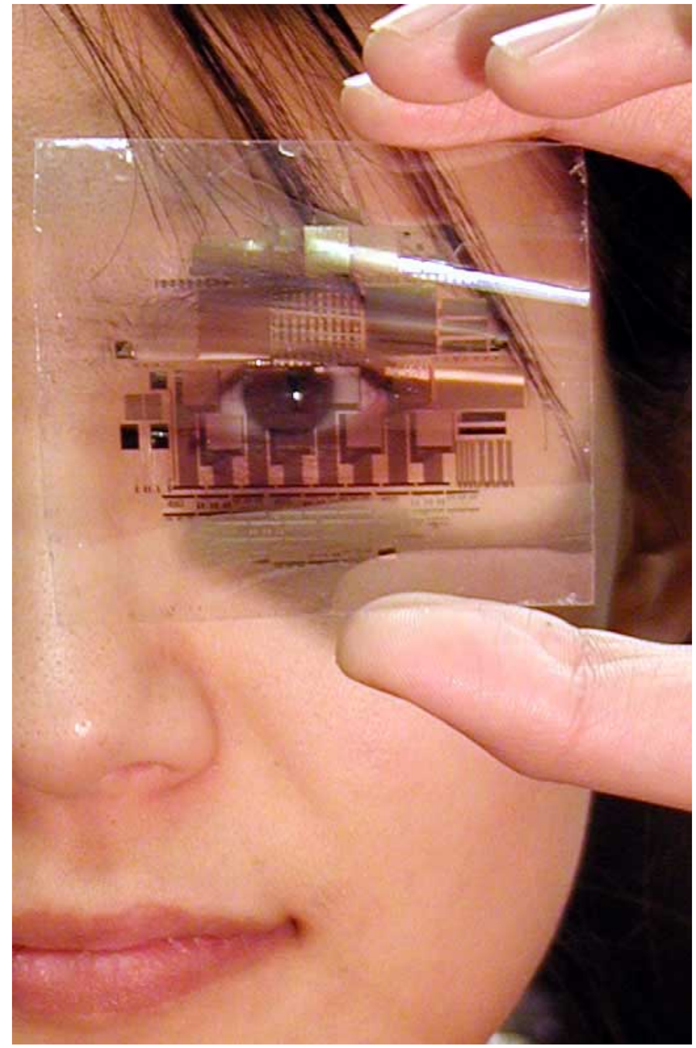


200 Transistor OTFT Array

Statistics for 1 cm^2 200 transistor array

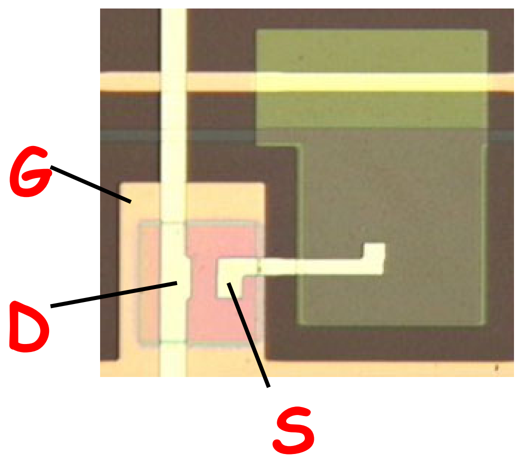
W = 25 μm
L = 20 μm





Mobility

average μ = 0.81 $cm^2/V\text{-}s$
σ_μ = 0.05 $cm^2/V\text{-}s$
for V_{DS} = -20 V



Threshold voltage

average V_t = + 1.8 V
σ_{Vt} = 0.8 V

On/off current ratio

10^6 .. 10^7

Collaboration with SARNOFF

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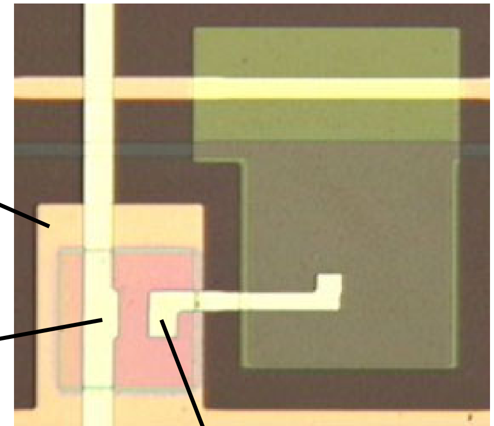
OTFT PDLC Display

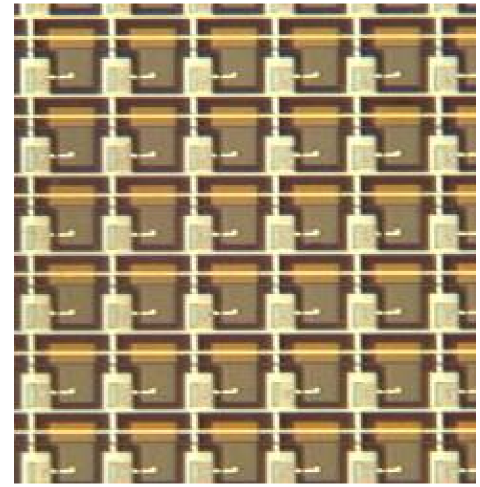
SARNOFF KENT STATE UNIVERSITY

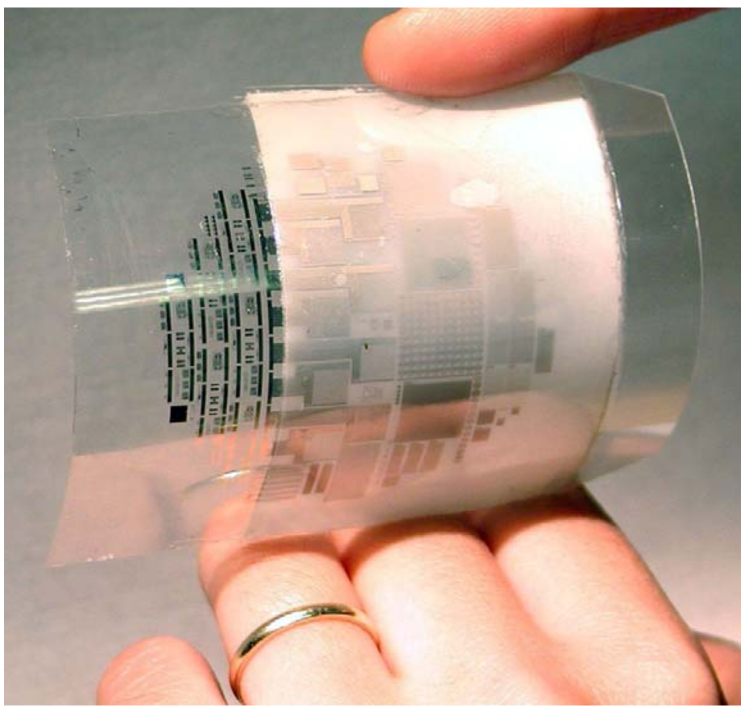
Active electronics will drive yield

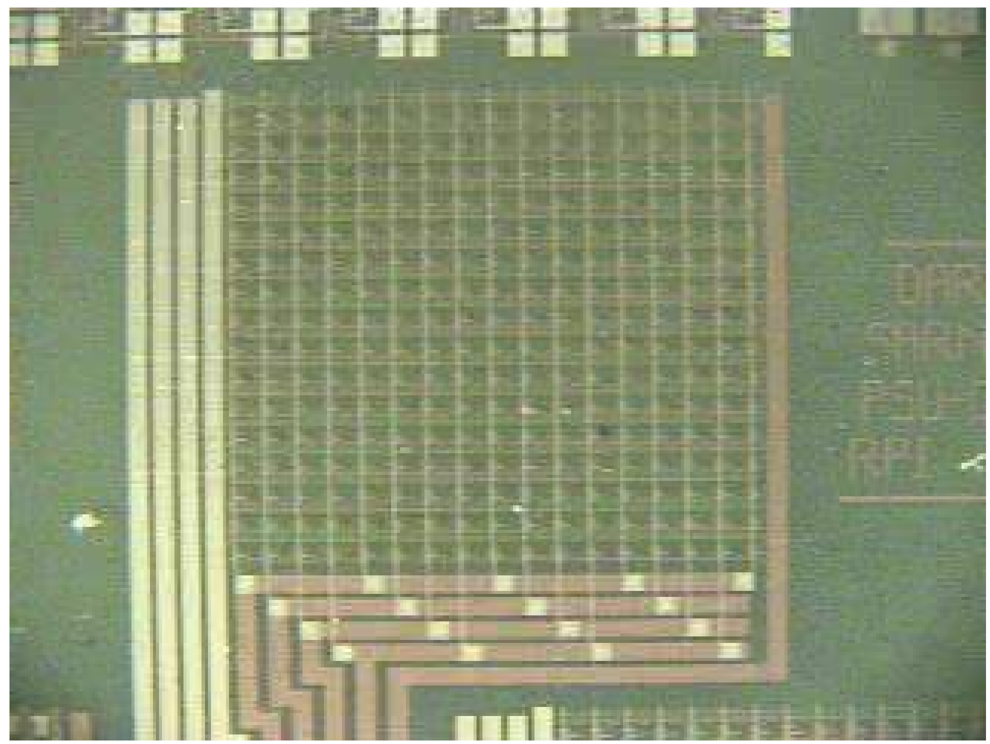
Organic TFT polymer dispersed LC display

- Simple repeating 4 x 4 layout
- ¼ VGA drive conditions (1/4 VGA):
  - 69 μsec line time
  - 60 Hz refresh rate
- Illumination 45°; black absorber









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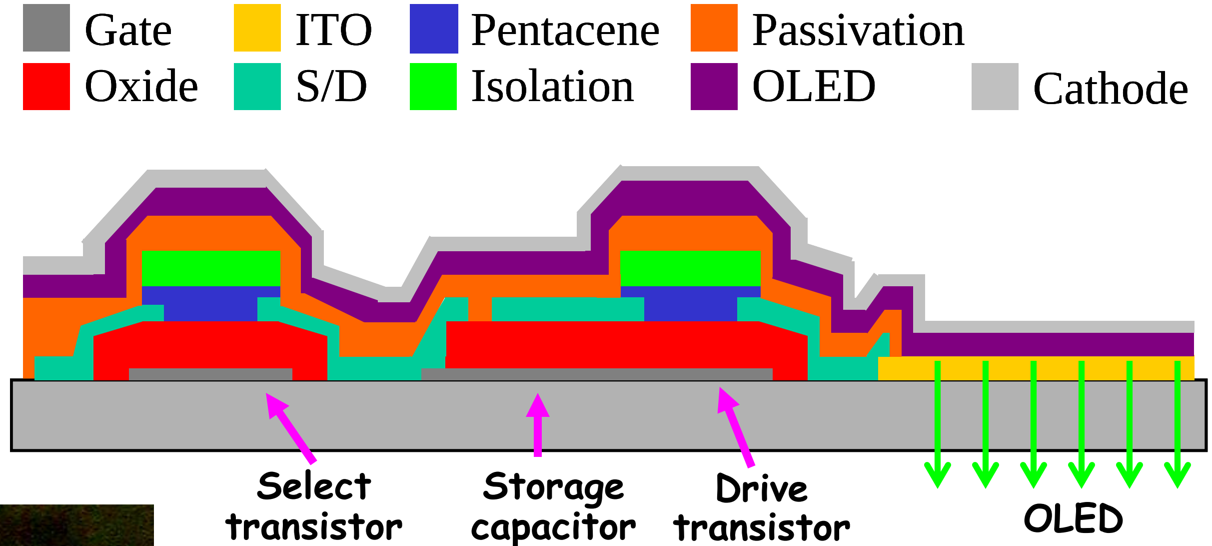
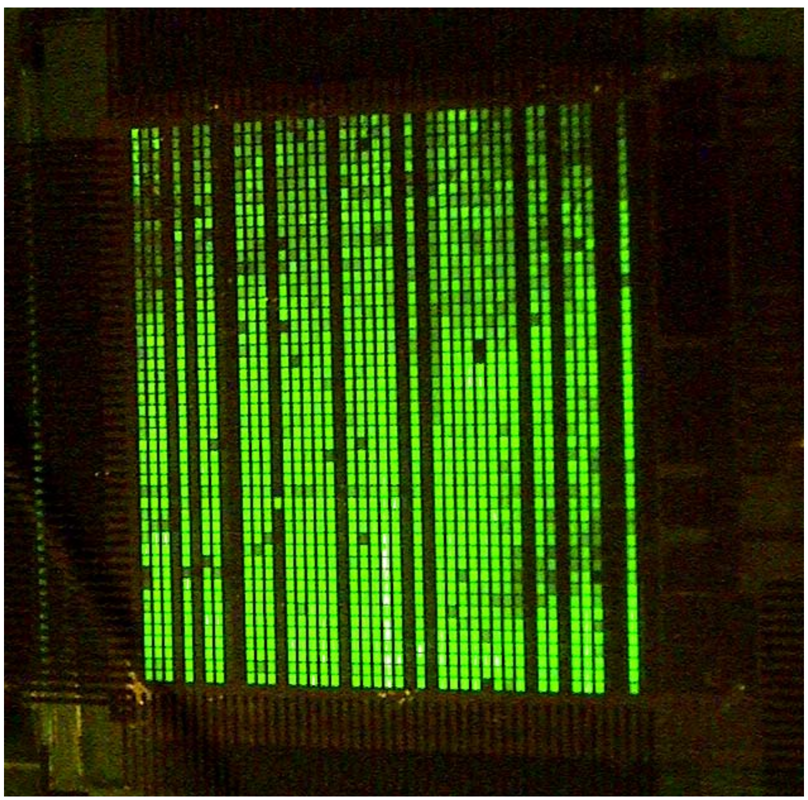
OTFT/OLED Active Matrix Display

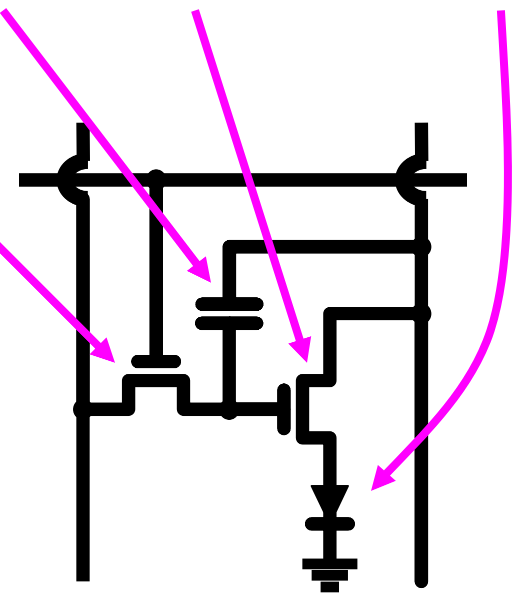
Photosensitive polyvinyl alcohol used for OTFT pattering and isolation

Parylene used to separate OTFTs and OLEDs





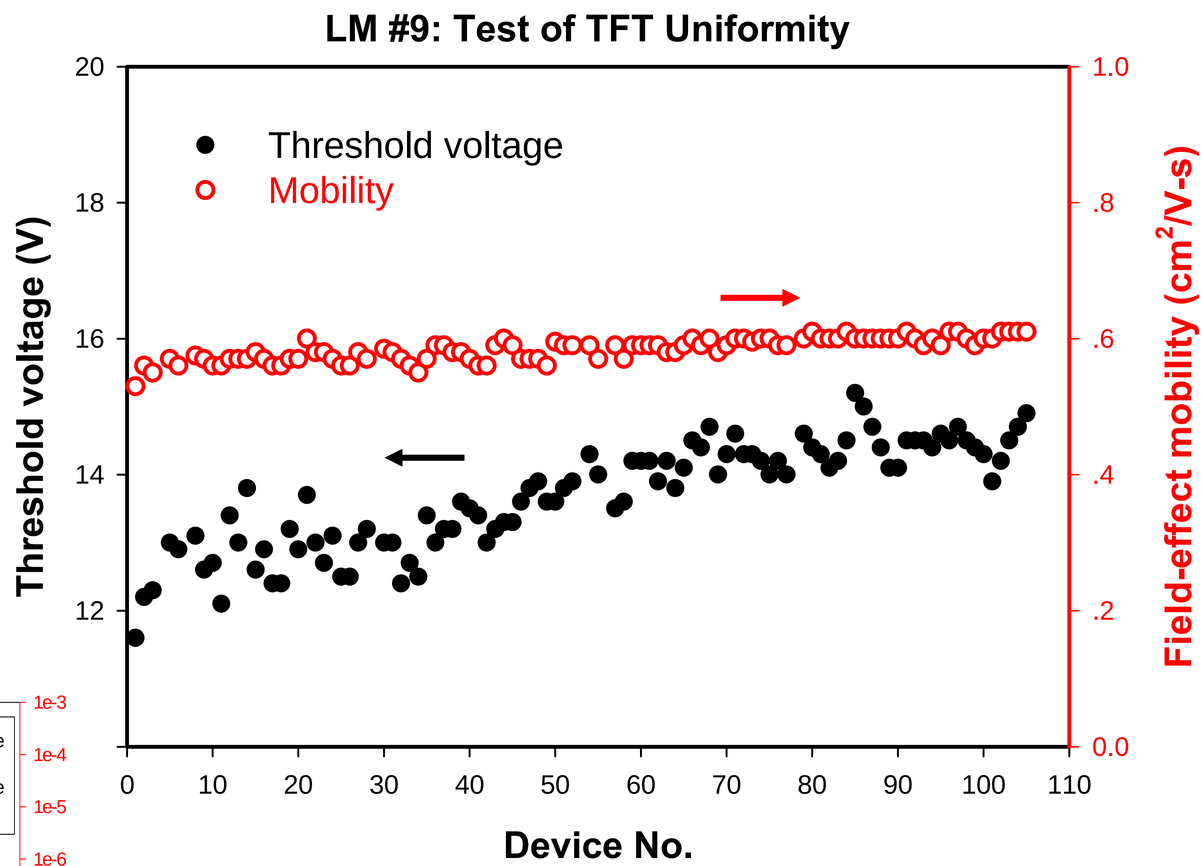
48 x 48 pixel array on glass

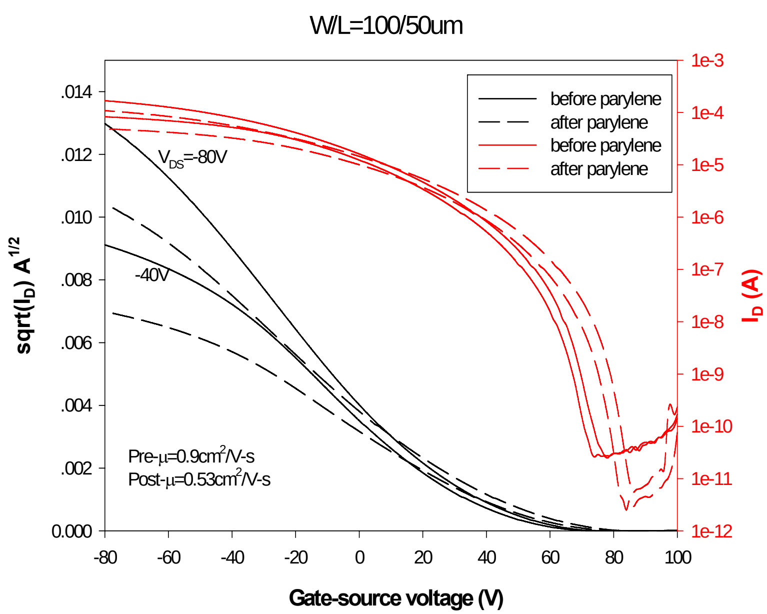


Simple two-transistor per pixel design

100 OTFT Array Uniformity Test

W/L=200/20μm
T_{OX}=300nm
Pt S/D bottom contact
PVA patterned pentacene
Parylene passivation





Average mobility = 0.584 cm²/Vs
σ = 0.017 cm²/Vs

Average threshold voltage = 13.7 V
σ = 0.78 V

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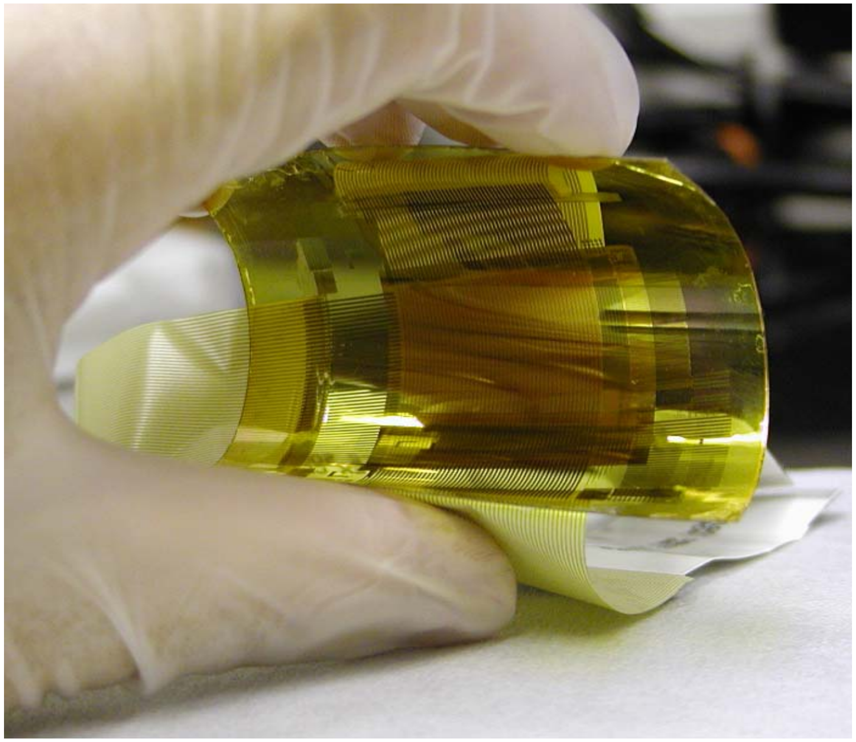
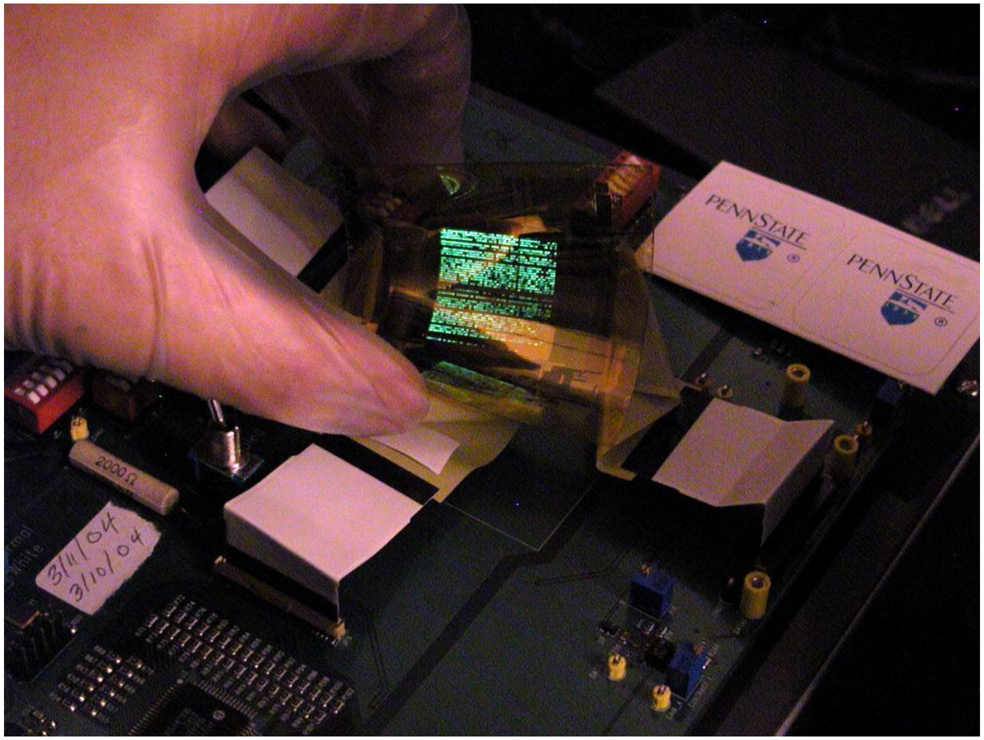
Flexible Substrate OTFT/OLED Active Matrix Display

- **PET substrate**
- **Pentacene OTFT backplane**
- **Parylene passivation**
- **TPD/AlQ$_3$ OLEDs**

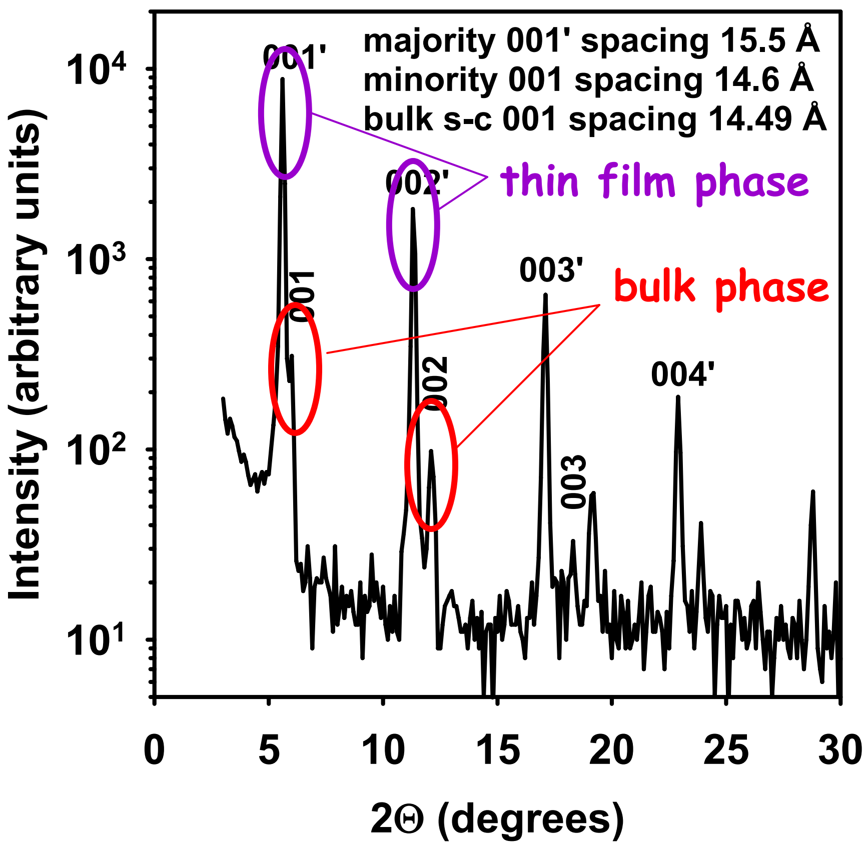


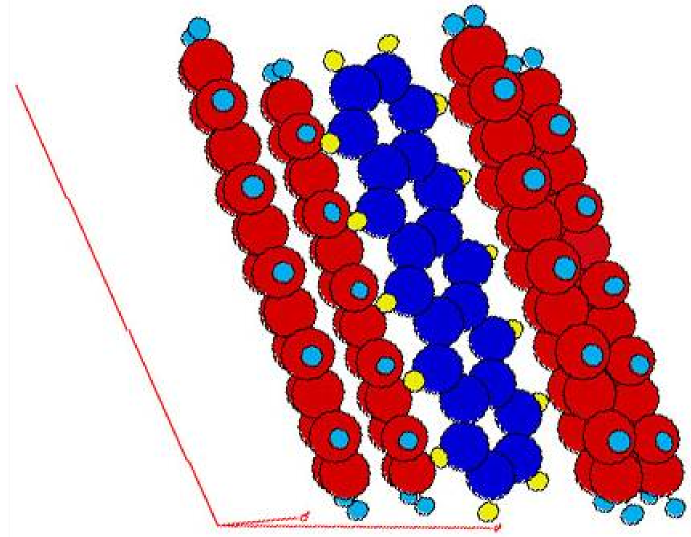


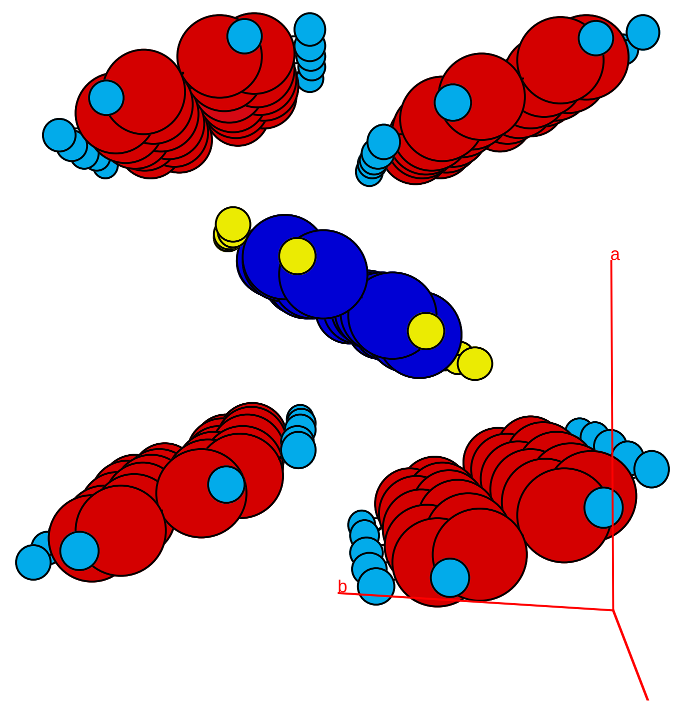
Improving Organic Semiconductors

Small-molecule semiconductors are typically weakly bonded molecular crystals

In pentacene this leads to a combination of face-to-face and edge-to-face interactions ⇒ minimal π-orbital overlap & poor electronic transport

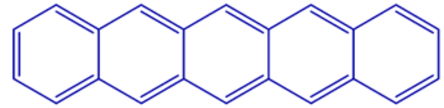






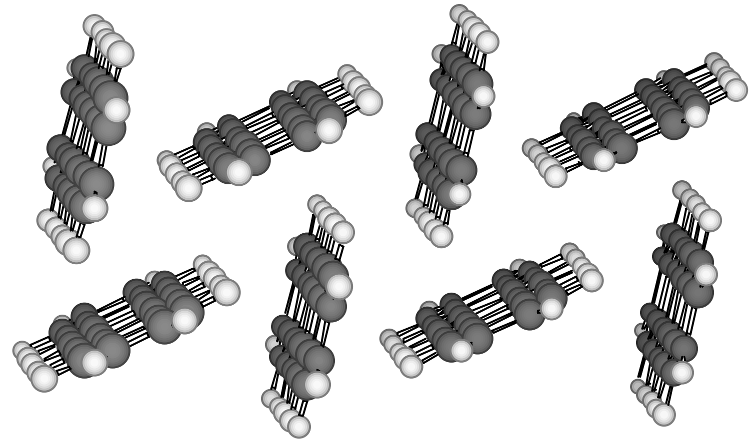
Improving on Pentacene

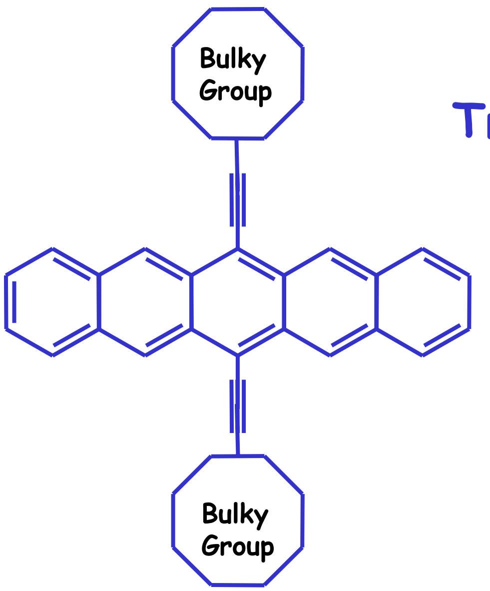
Pentacene derivatives



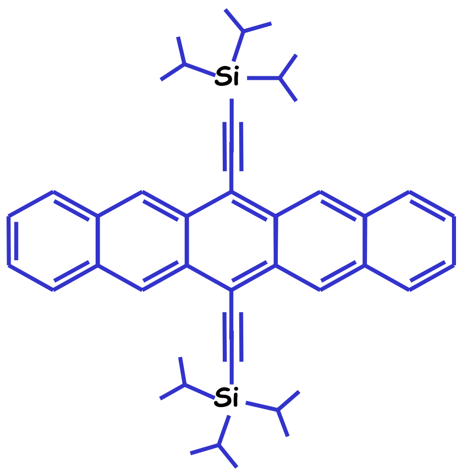
By substituting bulky groups at the 6,13 positions we can:

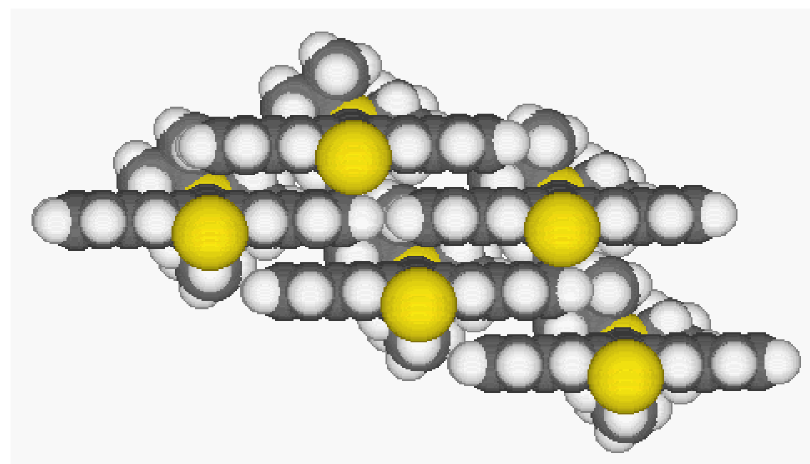
- Improve pi-orbital overlap
- <u>Allow solution processing</u>





Example:
Triisopropylsilylethynyl (TIPS) pentacene





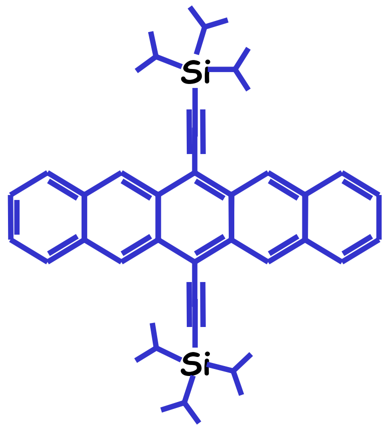
Collaboration with J. Anthony

University of Kentucky

Best vapor deposited field-effect mobility ~ 0.4 cm^2/V-s

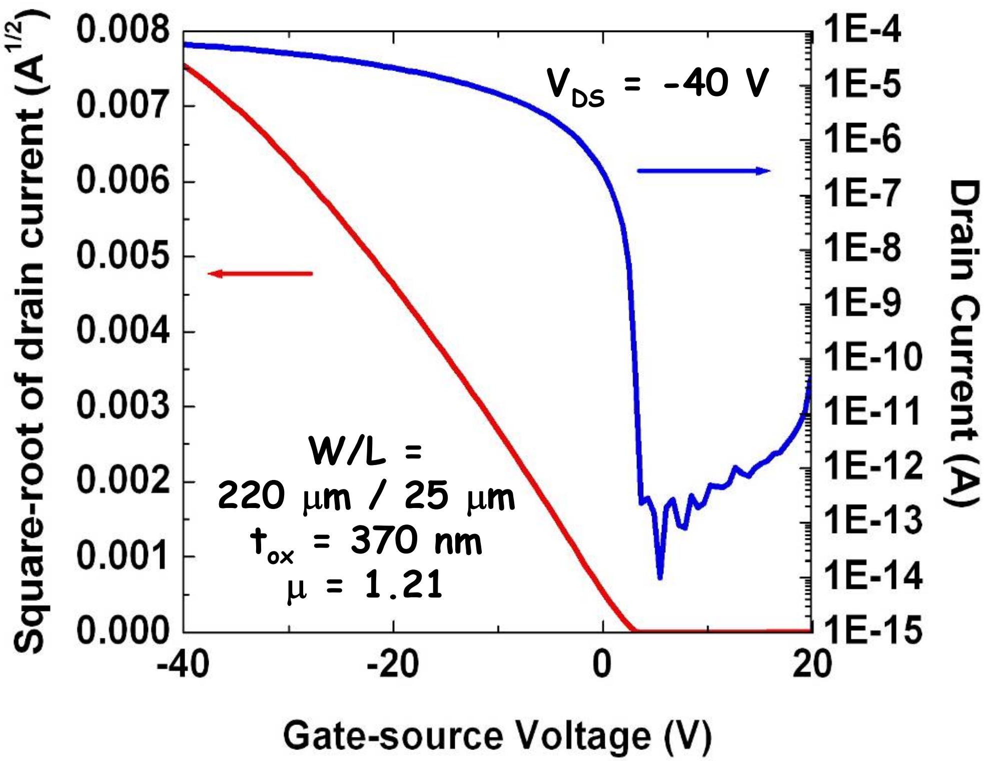
Solution Processed TIPS Pentacene

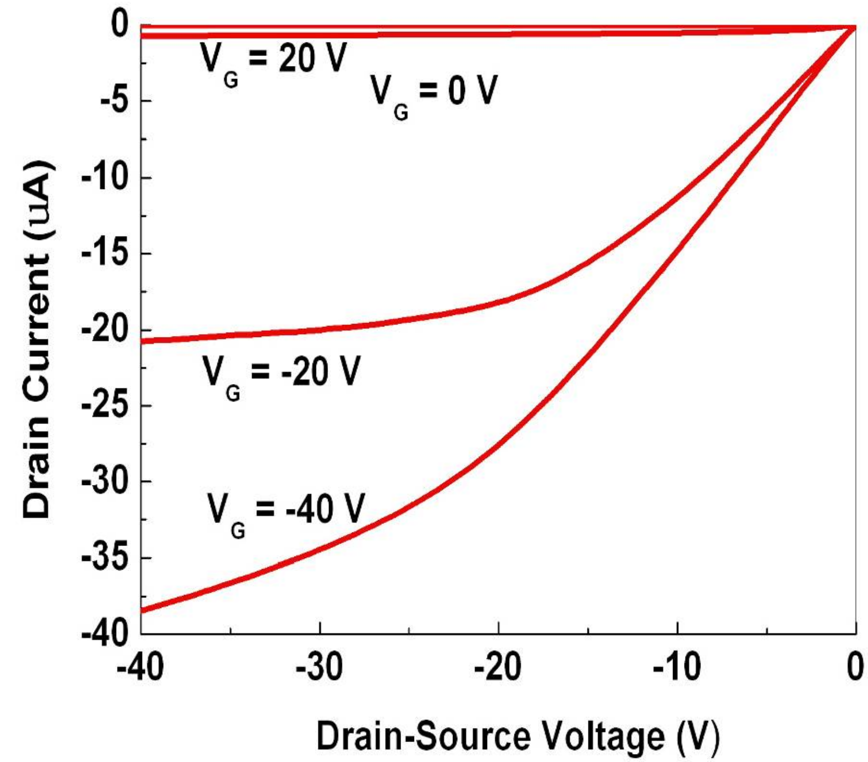
TIPS pentacene (triisopropylsilyl pentacene)



- Film thickness: 1000 ~ 5000 Å
- Drop cast from 1 wt% toluene solution
- HMDS dielctric treatment

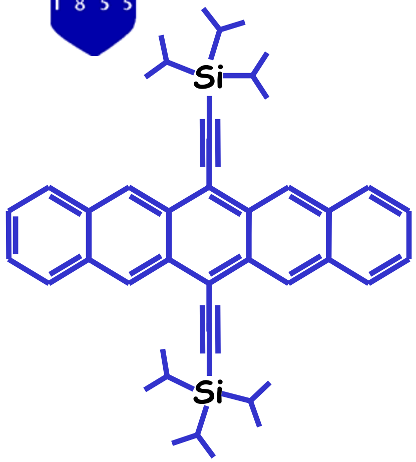
μ = 0.23 ~ 1.5 cm²/V·s, Vth = 0 ~ 5 V,
I_{on}/I_{off} = $10^{7\sim8}$, S = 0.3 ~ 0.8 V/dec.
μ > 3 cm²/V·s observed for a few devices





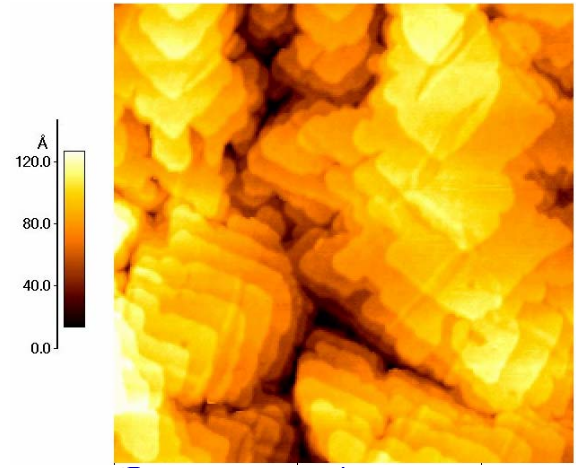
→ Very low cost active electronics

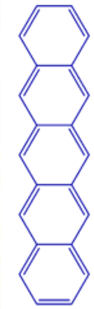
Molecular Ordering in Solution Deposited Films



Molecular steps in drop-cast and spin-cast films

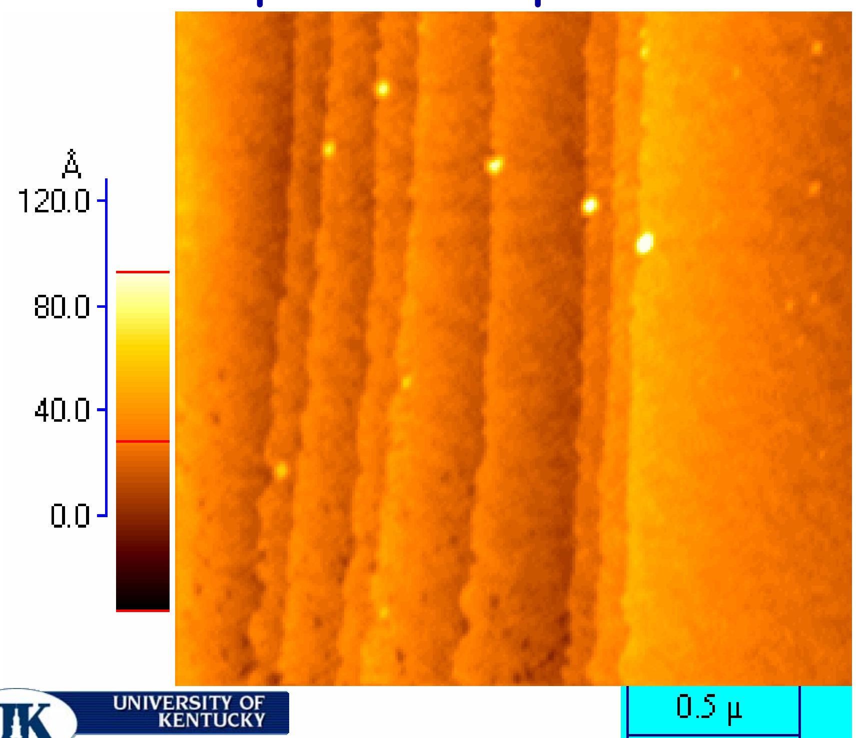
Solution deposited TIPS-pentacene films often have molecular ordering similar to vacuum deposited devices



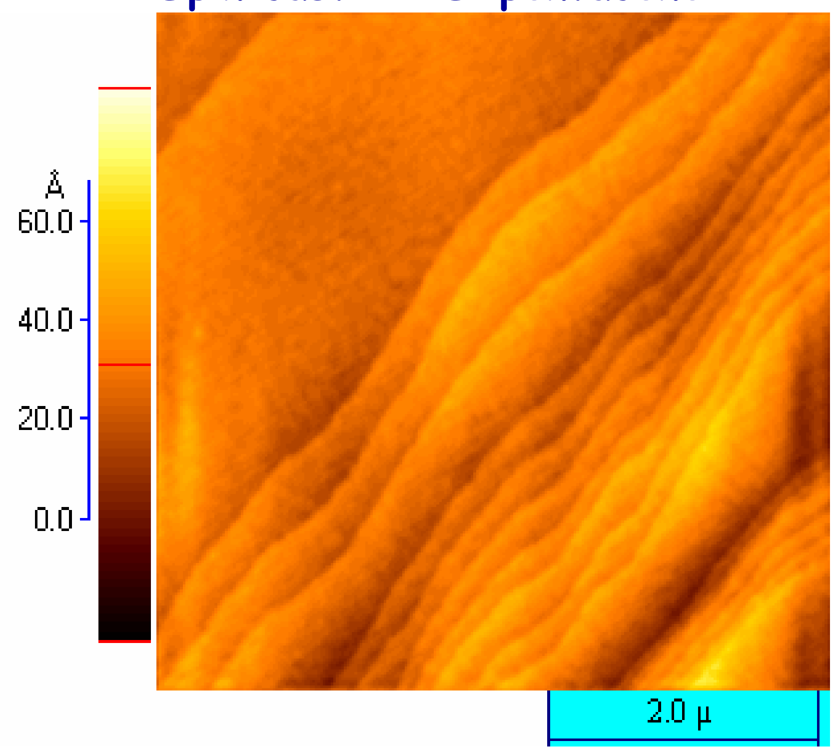


Evaporated pentacene

Drop cast TIPS-pentacene



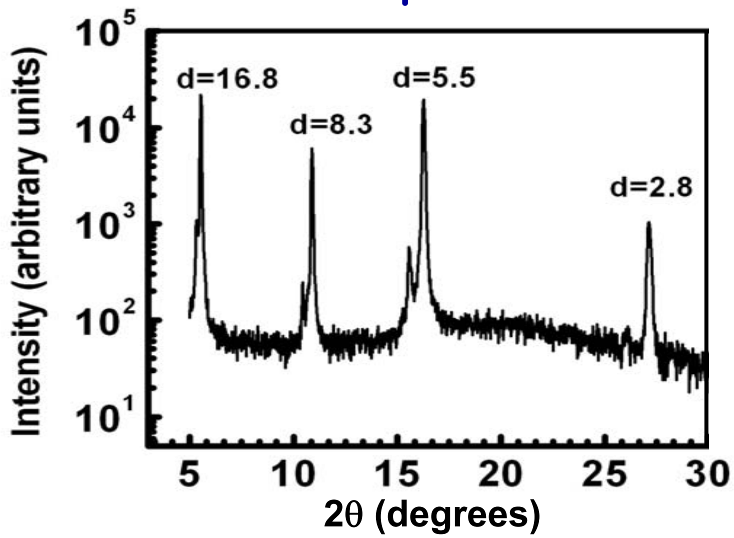
Spin cast TIPS-pentacene



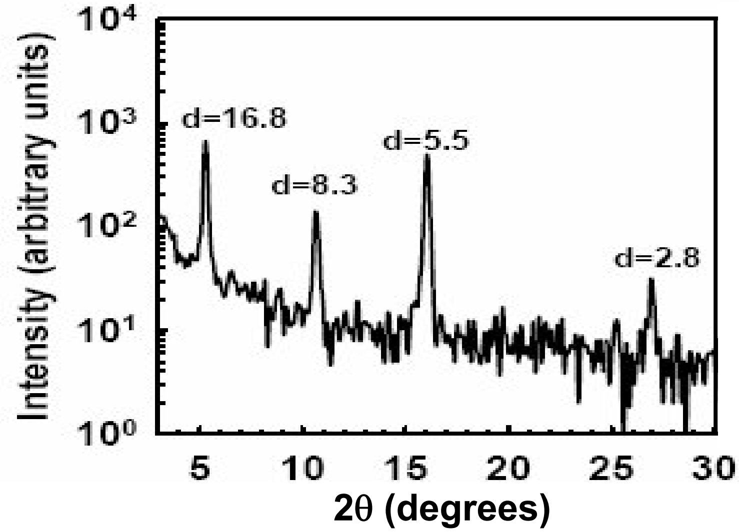
Molecular Ordering in Solution Deposited Films

X-ray diffraction for solution-deposited thin films very similar to single crystal

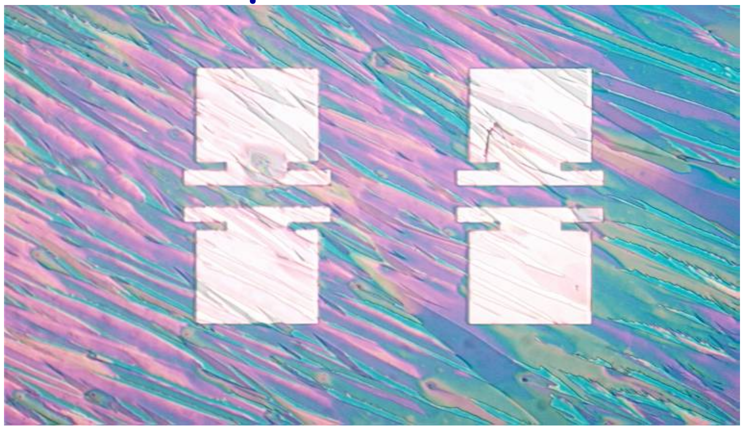
Solution-deposited TIPS



TIPS bulk crystal



Solution-deposited TIPS thin films



TIPS bulk crystal
(courtesy J. Anthony)

Macroscopic uniformity of solution deposited thin films fair to poor

Solution-Processed Device Uniformity

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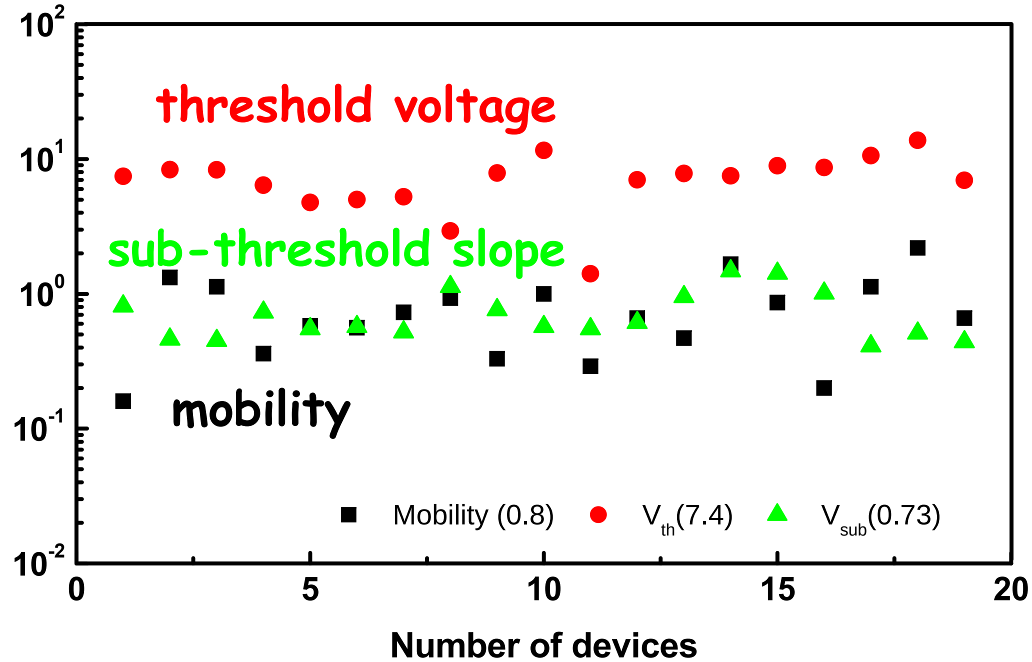
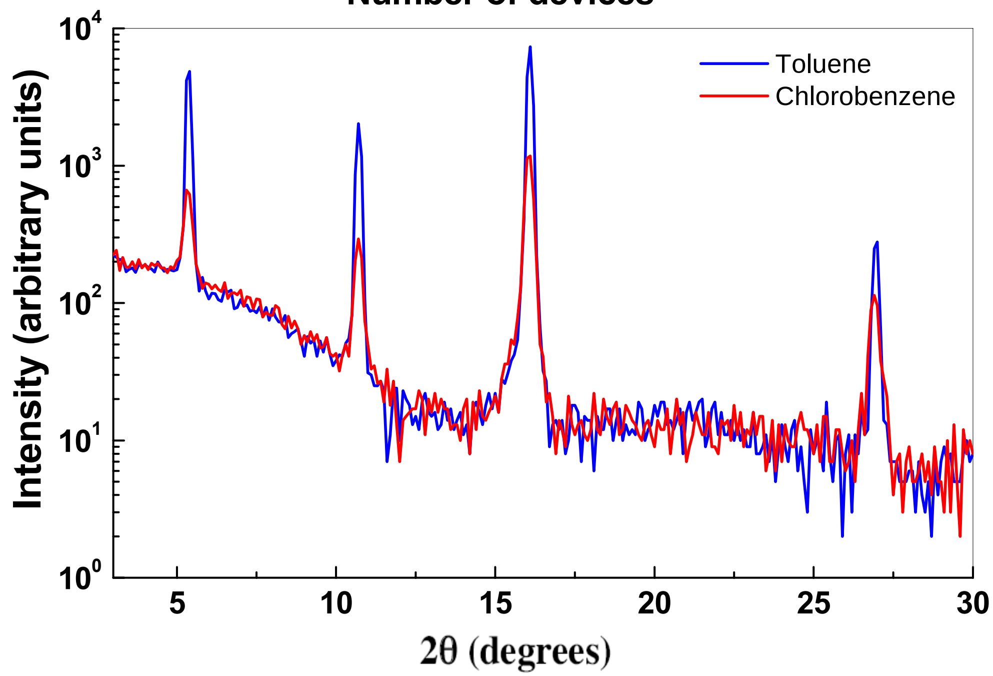
1855

Solution-processed device uniformity, reproducibility only fair, but improving

Device performance correlates well with film ordering

Film ordering sensitive to many factors – poorly understood





UK UNIVERSITY OF KENTUCKY

Organic Electronics Problems and Opportunities

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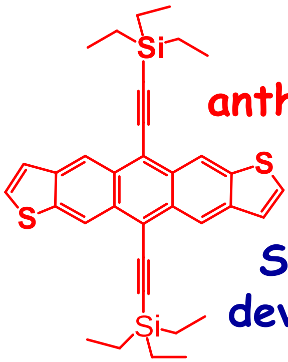
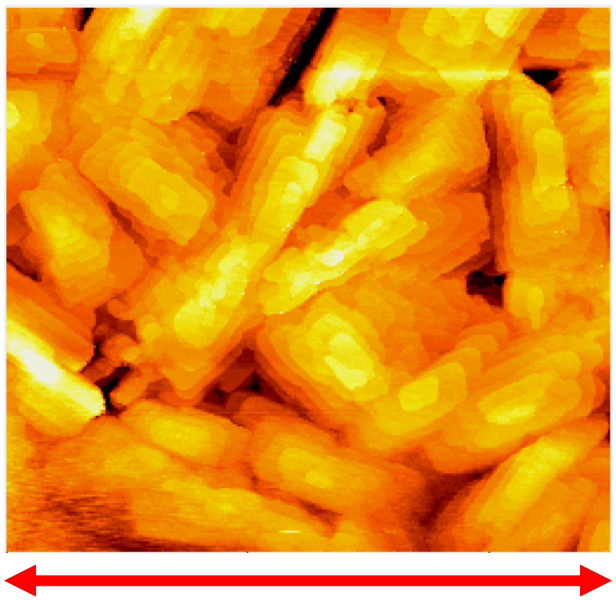


TES anthradithiophene

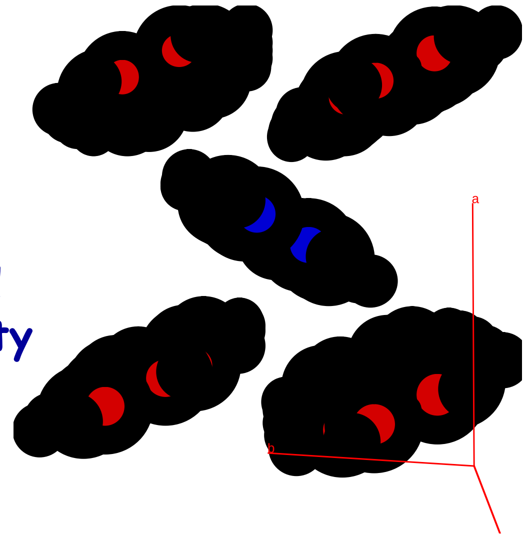
Solution deposited devices have mobility > 1 $cm^2/V \cdot s$

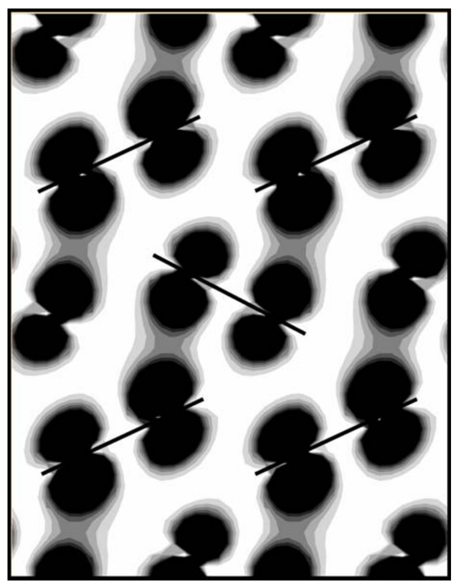


10 µm

80 nm evaporated TES ADT on OTS treated SiO_2

Well-ordered, but low mobility (10^{-3})





(K. Hummer, P. Puschnig, C. Ambrosch-Draxl, University of Austria, Gratz)

TFT current density

TFT: $Q = E_{gate}\, \epsilon_{ox}$

SiO_2 $\epsilon_{ox} = 3.9\epsilon_0$, $E_{max} = 10^7$ V/cm

$Q_{max} = 3.5 \times 10^{-6}$ C/cm^2
$= 2.2 \times 10^{13}$ $carriers/cm^2$

Sheet resistance of a sheet of charge $R_s = 1/(q\mu N_{sheet})$ Ω/□

Suppose μ = ~1 $cm^2/V{\cdot}s$

$R_{smin} = 1/(q \times 2.2 \times 10^{13}) =$
~2.8×10^5 Ω/□

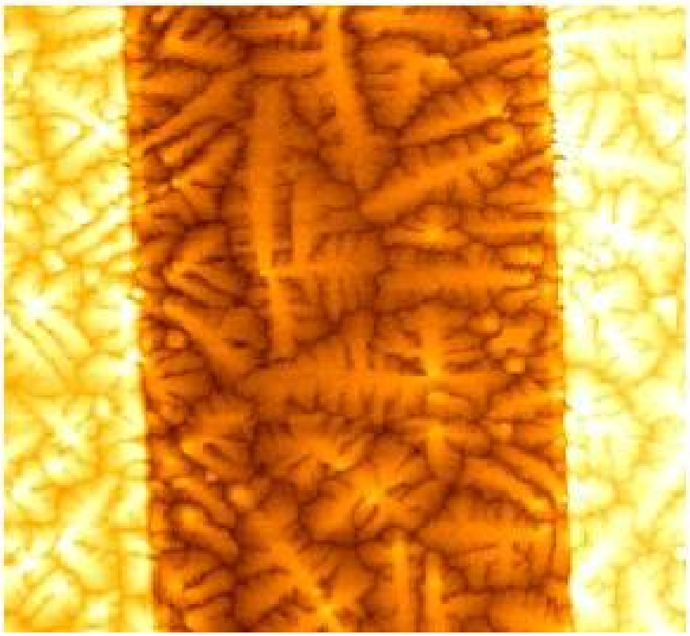
Suppose L = 1 µm & V_{DS} = 10 V

Then I_{DS} ~36 µA/µm or 0.36 A/cm

But channel is thin, ≲ 10 nm, so this is a current density of about $3.6 \times$ $\underline{\underline{10^5\ A/cm^2}}$

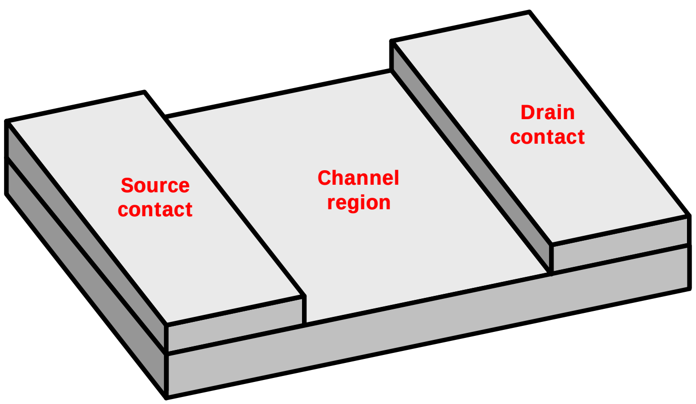
Compare: OLEDs ~1 A/cm^2
organic laser ~1000 A/cm^2

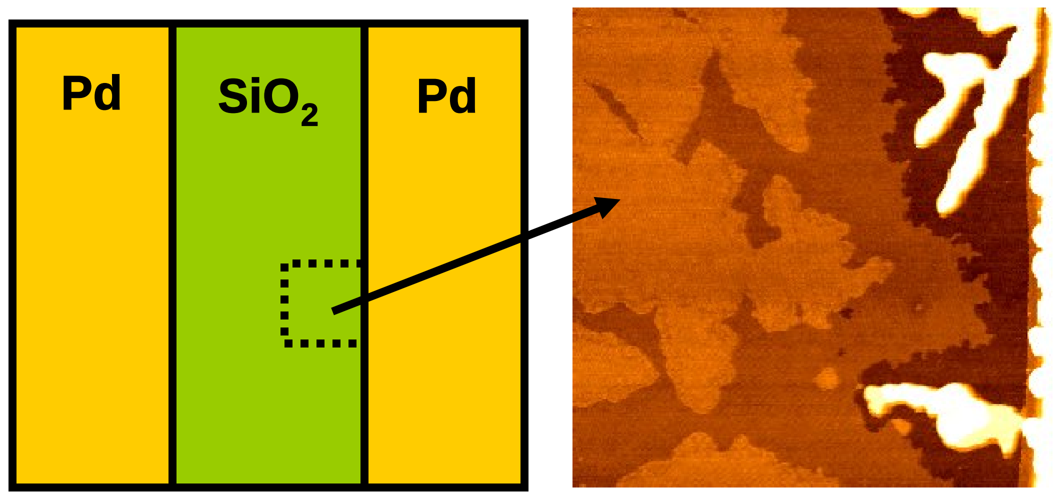
Central Problem #1 - OTFT Contacts



Most organic semiconductors look a lot like insulators – contacts can be problematic

Details of film growth and morphology and device structure often amplify contact problems





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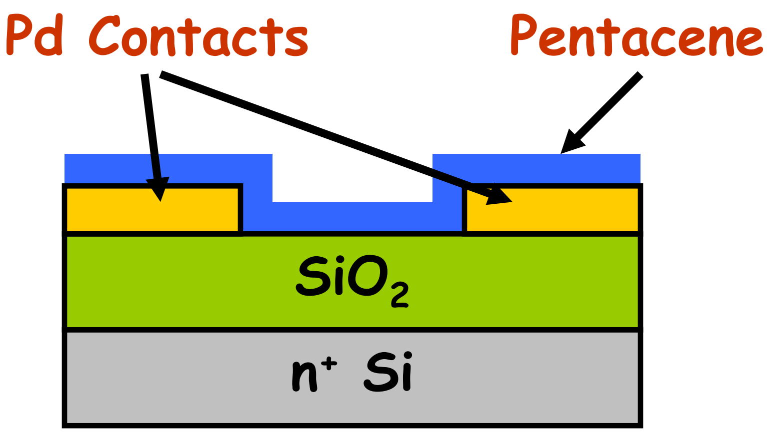
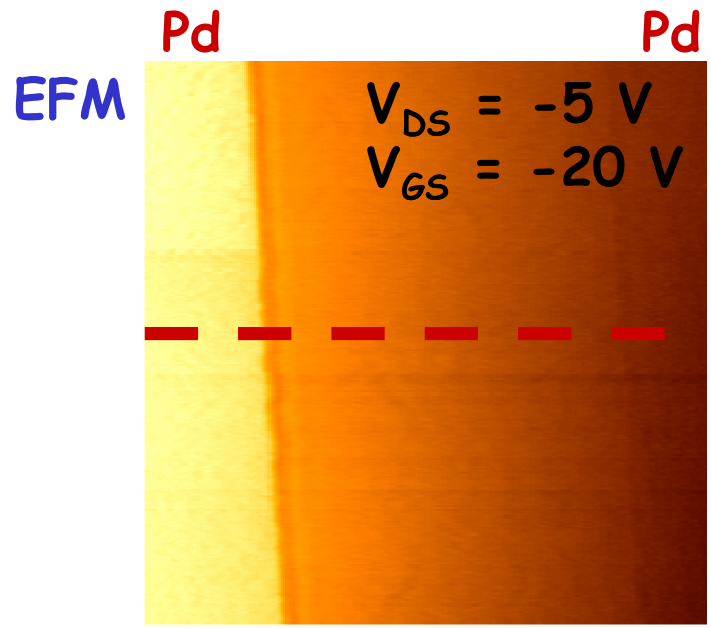
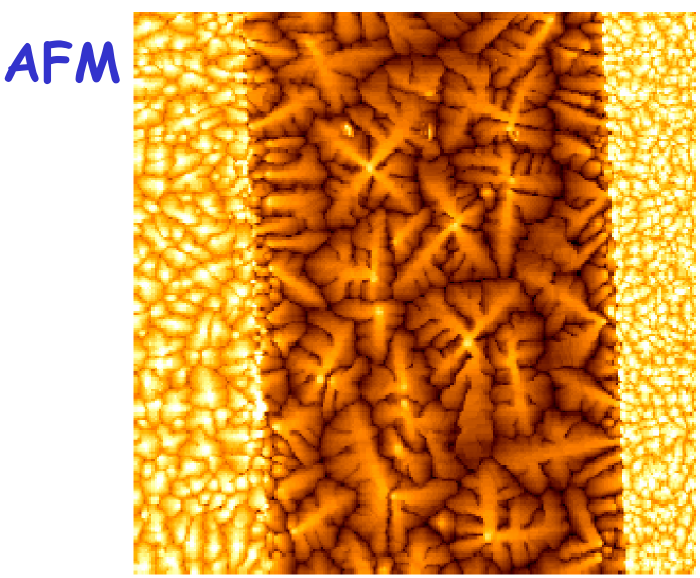
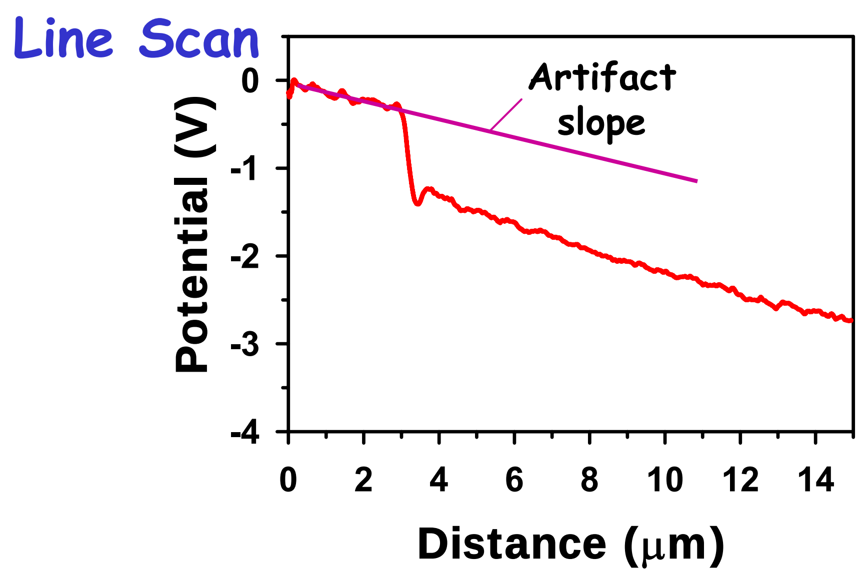
OTFT Contacts – Potential Imaging



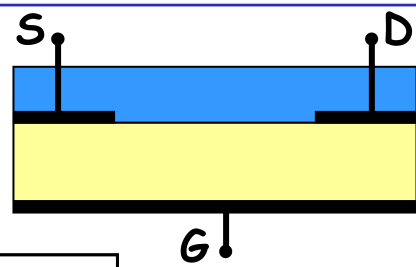
Bottom Contact TFT

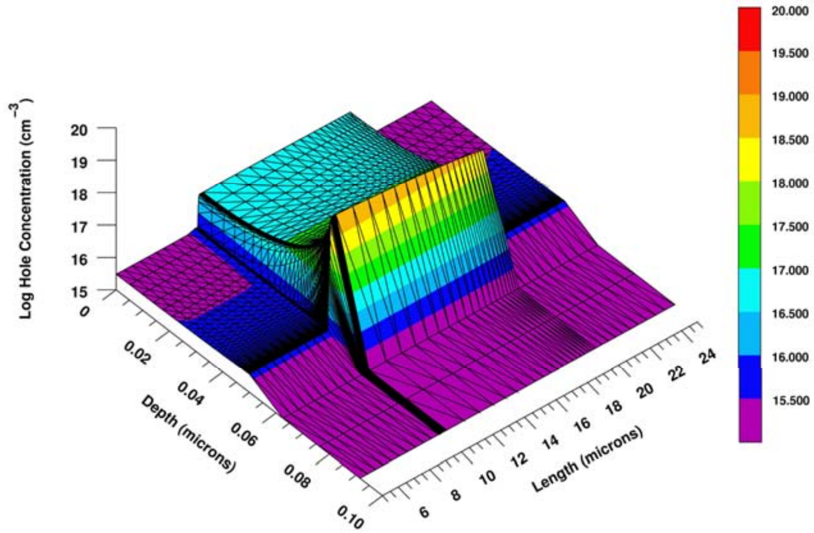


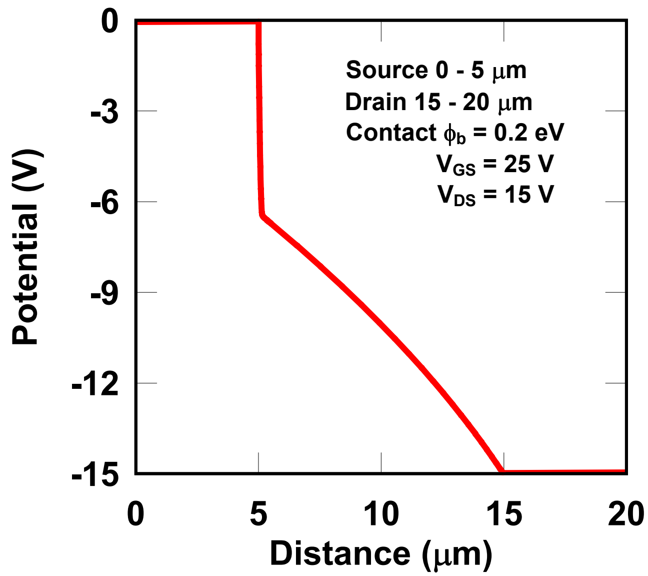


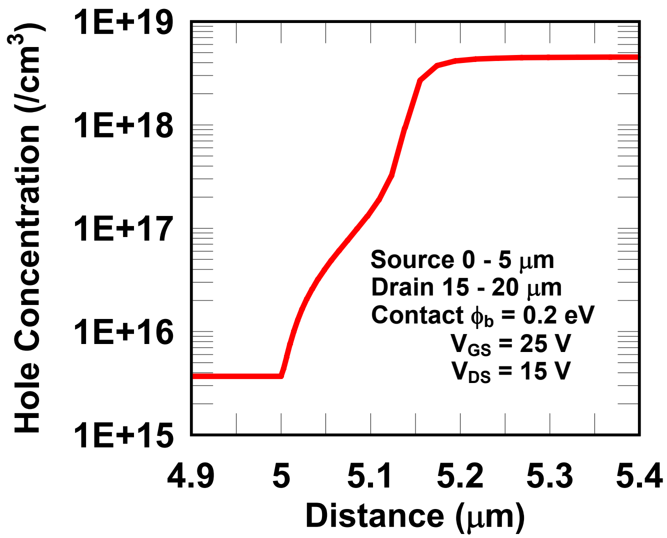


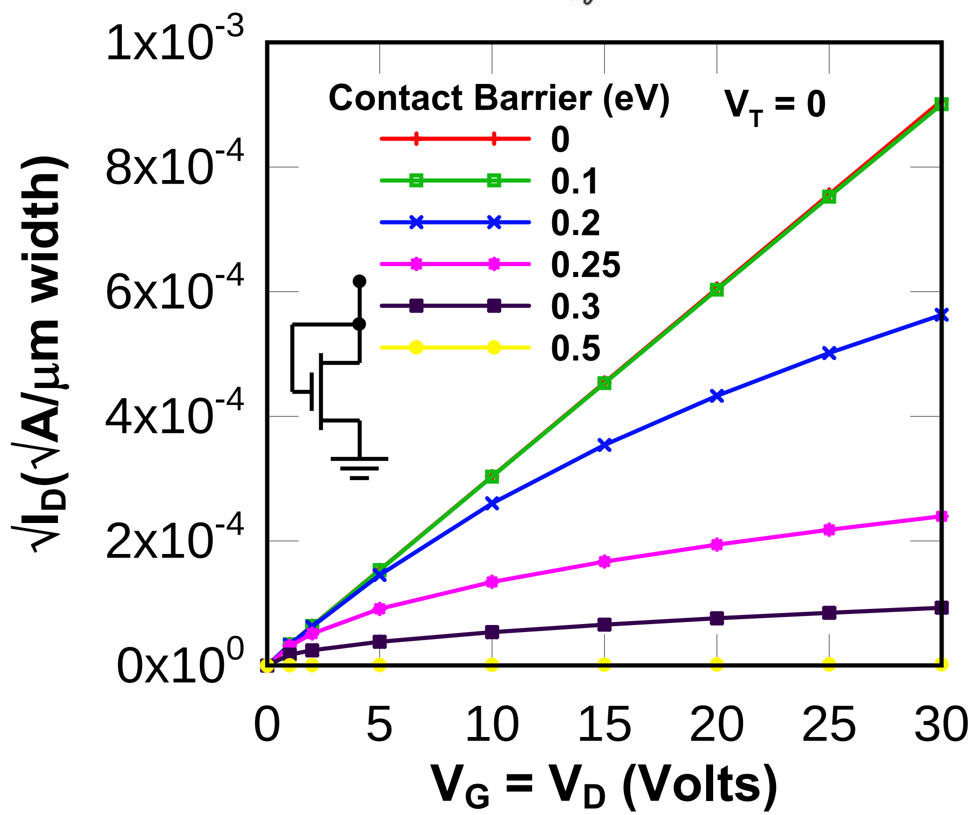
Contact Barriers



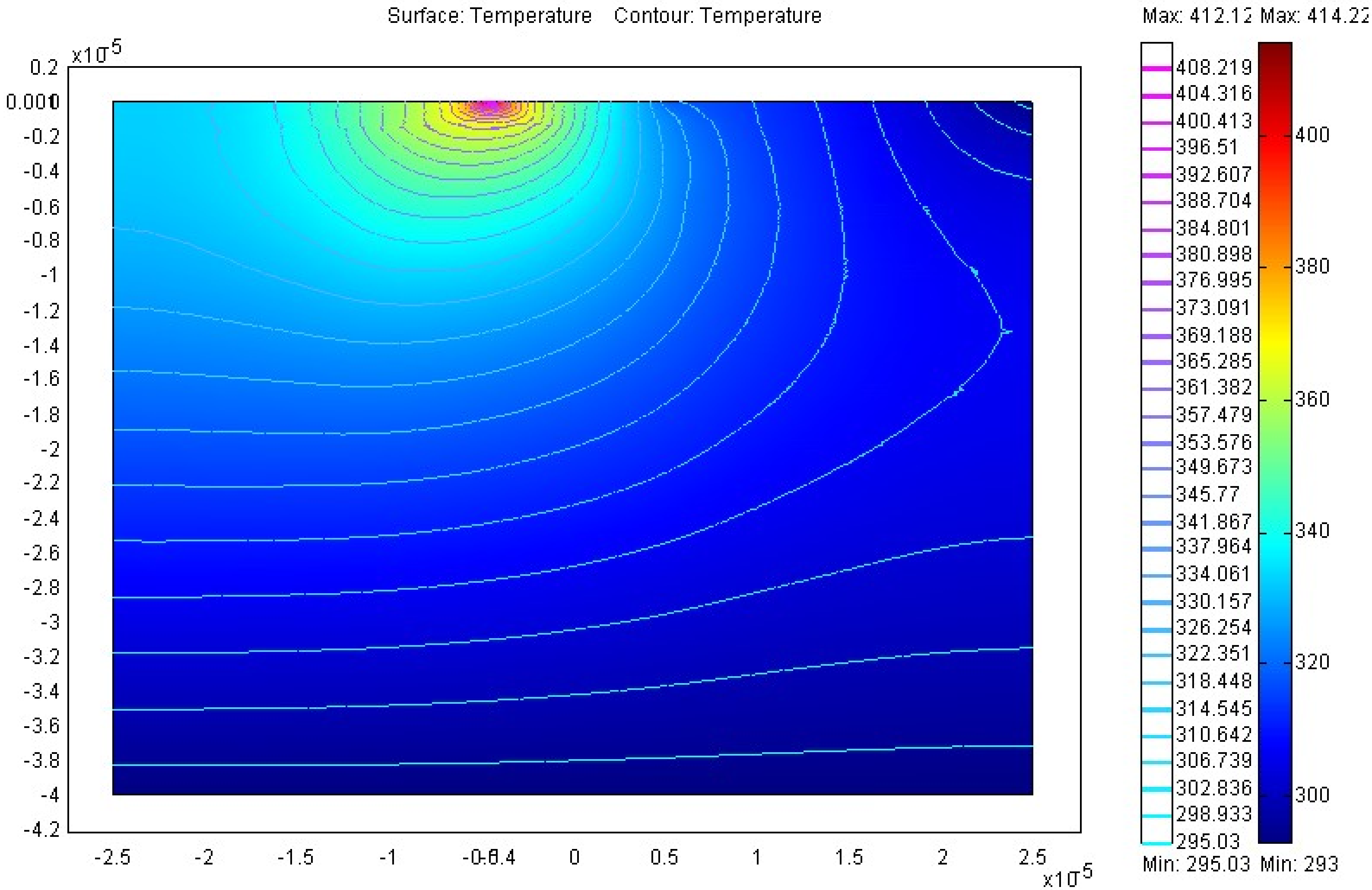








Contact Related Power Density



Central Problem #2 - Dielectrics

Lots of Applications

Lots of central problems?

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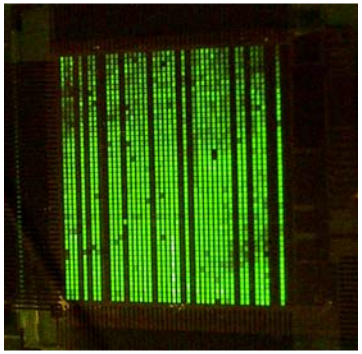
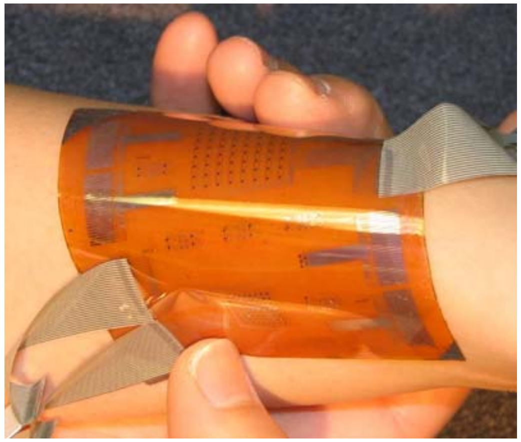
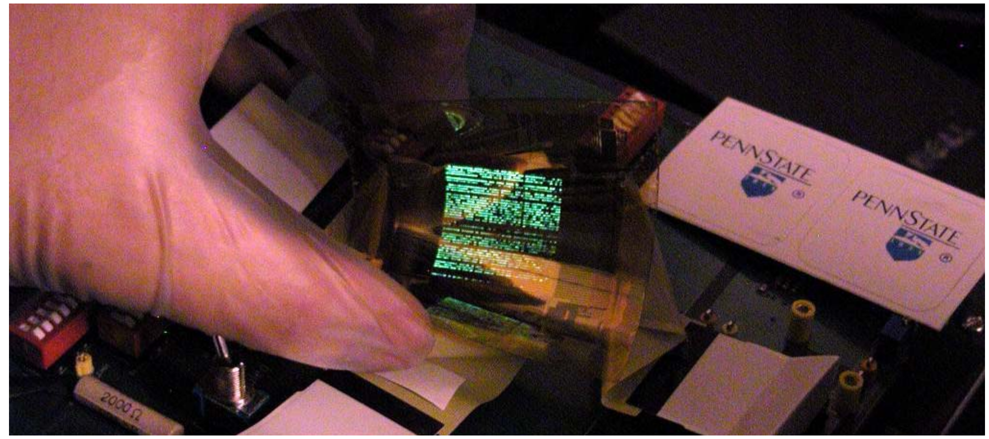
Flexible Large Area Electronics and Photonics







- Polyimide substrate a-Si:H AMOLEDs
- ZnO conductors and semiconductors
- Polyester substrate organic circuits
- All organic displays
- High mobility solution-processed devices
- Improved materials likely
- Steps toward electronics anywhere!
  - cost? cost? cost?